Autonomous aerial vehicle: flight control and energy management

Report

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1 Aim

The finality of this project is to study and evaluate the use of a redesigned and modified UAV for first aid assistance in rescue operations.

2 | Scope

The scope of the project is defined below in order to achieve significant results regarding the aim of the project.

- **Vehicle**
  - Selection of suitable UAV type to perform the mission.
  - Selection of the hardware needed: engines, flight controller, communication system.
  - Design an UAV by adapting an existent one or building it.
- **Energy source**
  - Calculation of power and energy needed and selection of a suitable power source.
  - Feasibility study of the implementation of a renewable energy system to increment the available energy.
- **Energy management**
  - Design/selection of measurement electronics.
  - Design/selection of control electronics.
  - Elaboration of an algorithm to make the parts of the UAV work together efficiently.
- **Prototype**
  - Integration of a Prototype.
  - Experimental tests and validation.

Base station and auxiliary equipment for ground handling operations such as programming, charging and maintenance of the UAV are not included in the project.

3 Requirements and technologies

In this section the requirements and the technologies to fulfil them are stated in order to be developed during the project.

3.1 Requirements

Requirement	Description
1	The UAV has to be capable to maintain a **forward flight** and a **hovering flight.**
2	The UAV has to have a range of operation of **10 km**.
3	The UAV has to fly **autonomously**.
4	The UAV has to be capable to **send information** to a control ground station about the performance of the mission.
5	The energy of the UAV has to be **managed efficiently** in order to achieve the target or, if not, it has to be capable of **landing safely**.
6	In case of **crash**, this event has to be **detected and the engines stopped** to avoid major damages.

Table 3.1.1: Requirements of the project

3.1.1 Technologies to fulfil the requirements

1. **Multi-rotor UAV:** The critical type of flight that decides which is the kind of UAV needed for this application is the hovering flight. For having an UAV capable of flying without forward speed a multi-rotor is needed.

2. **Suitable selection of battery and possibility to include a photovoltaics generation system:** In order to achieve the specified range, the battery needs to be chosen according to the amount of energy and power required and also to the weight of the UAV. In this project an UAV will be designed taking into account the critical case of needing a range of 10km. However, this same UAV can have different ranges by changing the battery, so it can be said that what will be created is a family of UAV with different ranges depending on the battery size. The amount of energy provided by the battery can be increasing by obtaining energy during the flight. In order to do so, photovoltaics technology is

proposed. A study will be done about what type of photovoltaic cell best fits the needs of the UAV, taking into account the space the former has to install a photovoltaic cell. A study whether implementing a photovoltaics system is profitable or not will be done.

3. **Flight optimization:** An algorithm to optimize the flight of the UAV will be created to save as much energy as possible. With this optimization, the range could be increased. This algorithm will also create the file with the commands to be followed by the UAV so the only thing needed to do will be update the file to the flight controller.

4. **Autonomous flight:** To fly autonomously a waypoint navigation will be used. To perform this type of navigation, a suitable flight controller that accepts this flight mode is needed. Also, some sensors are needed to perform this type of navigation.

5. **Wireless communication:** A wireless communication between the UAV and the station is needed. In the mountainous regions at which the UAV will perform its activity and at the specified range, most of the normally used communication system are not useful. Alternative systems as GSM and satellite communication will be evaluated in order to select which one is more suitable for the application.

6. **Generation of a map with the positions of the UAV and creation of a database:** To store and shown the information that the UAV sends using the communication system, an algorithm will be elaborated in order to create a map with the lasts positions of the UAV and store it in a database.

7. **Design of the management and control electronic and proper configuration of the flight:** To manage efficiently the energy, management and control electronics should include all the necessary components to achieve a correct behaviour of the system composed by the photovoltaics, the battery, the engines and the flight controller. Sensors such as voltmeters will also be studied in order to know the state of the battery. A proper configuration or modification of the flight controller is also needed in order to make the UAV land safely when the safe battery operation range has been surpassed.

8. **Crash detection:** The flight controller has to be capable of detecting a crash and stop the engines as a security measure.

4 Justification

In the year 2015[1], 1563 mountain rescues to people were needed in Spain. The results of this rescues were[2]:

- 958 (61,3%) uninjured
- 502 (32,11%) injured
- 103 (6,59%) deceased

The causes of these rescues had been mainly falls, loss or physical problems that did not allow the hiker to arrive to its destiny. The cost of one of these rescues is usually expensive and depend on a lot of facts. The time that can take to carry out a rescue can vary from half an hour to 3 hours or more. Moreover, there are cases in which the rescue has to be postponed to the following day due to poor visibility or adverse climatic conditions. An hour of one person of the rescue personal costs about 40€, and an hour of a terrestrial vehicle 50€. If only this fact is taken into account, the rescue can result very expensive. However, in some of the cases, an helicopter is needed due to the difficult access to the terrain and the existent hurry to rescue someone. The cost of an hour of helicopter is approximately of 3000€. It is clear that the fact that can increase exponentially the cost of a rescue is the use or not of one or more helicopters.
It is also important to say that the number of rescues needed is increasing during the last years, as can be seen in Figure 4.0.1. The experts agree that this increase is due to, in some part, the fact that the number of hikers are increasing due to two effects called "Decathlon" and "Calleja". However, the fact of more rescues needed seems to deal to the expansion of smart phones as the main cause. Primitivo Hernández, colonel of the mountain service of Jaca from the Civil Guard of Spain, explains *"The rescues shot up during the nineties. People have a device with they can use to ask for help and use it when they feel at risk. It is true that there are times when it seems that the rescued ones could have gone on their own feet, but it is impossible to know what would have happened in the case of the Civil Guard did not appear."*
As it has been exposed previously, most of the rescues where to uninjured people, probably lost in the mountain and exposed to drastic climatic conditions (freezing temperatures during

[1] It is the last year of which information is available
[2] Information has been extracted from [3].

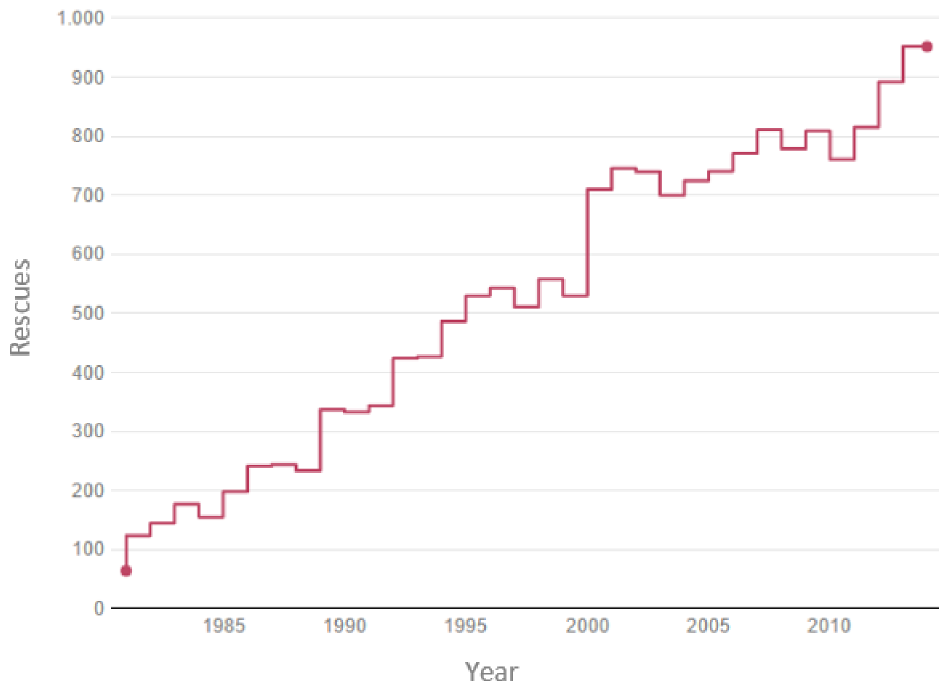


Figure 4.0.1: Rescues needed in Spain during the last decades. Image extracted from [3].

the late afternoon and the night). There has been cases at which the helicopter had been used but it was not necessary, because if the hikers had been able to wait some hours at their situation a team on foot could have been sent. Here is were the UAV can have a real and useful implementation. Providing the hikers of some material as a thermal blanket and a power gel, the rescue team would have a margin of time to think whether is there a real need to use the helicopter or not, then reserving the use of the helicopter for a real dangerous situations and thus contributing to a more rational use of resources. Arrived at this point, there are still some questions to be answered.

- **Why an UAV?** It is a flight vehicle and, equally to the helicopter, it can move satisfactory through mountainous terrains.

- **Where the UAV takes off?** The idea is to create a network of small mountain stations, big enough just to keep inside the UAVs needed for the terrain they are taking care of. In regions like Huesca, where the 36% of the rescues take place, 3 rescues can took place in a single day, so more than one UAV capable of communicating to others in order to organize the missions will be needed. With stations' network located in the mountanious region, the time the UAV will take to arrive to the person who has to be rescued will be reduced significantly compared with the time it will take to arrive from outside of the region station. Solar panels will be added to the station in order to power it and also to charge the battery of the UAVs. Knowing that helicopters have a carboon footprint between 6 and 12 kg CO2e/km [4], the fact of charging the UAV using green energy will also reduce the contamination and its impact on the natural medium.

- **Who will pilot it?** The UAV will flight autonomously. The GPS signal of the person that needs the rescue will arrive to the rescue team, and a remote computer will send it to the nearest UAV's station together with the path they have to follow in order to consume the less amount of power possible.

- **What problems need to be solved?**
  - The autonomy of a standard UAV is nowadays more or less 10-20 minutes. With this autonomy the range of the UAV is quite poor, so in this project an study to improve this field will be done. The autonomy of the UAV can be increased doing a correct design of the UAV for the specific mission this project deals about. Moreover, a careful selection of components such as the battery will be done and the implementation of a system to obtain renewable energy during the flight will be studied.
  - An effective communications system has to be chosen in order to communicate only when needed (not communicating continuously and spending power unnecessarily). It also has to be capable of communicating in the specified range and in the region the UAV has to work, the mountain, where communication problems can appear.

What will be done in this project is to test if a redesigned UAV is capable of do this kind of mission. To do so, the studies explained in the previous paragraph will be carried out. Is important to say that for a real application in a mountainous range, the UAV has to be selected according to the needed range, the climatic conditions, etc. In this project experimentation will be done regarding the obtaining of energy and the optimization of its use. For the realization of this project knowledges of aerial navigation, fluid's mechanics, automatic control, electronics and computing are needed.

5 State of the art

UAV are the initials of Unmanned Aerial Vehicle and, as its name says, is an aerial vehicle that flights without a crew onboard. The flight of an UAV can be done with different degrees of autonomy, from a remote control flight to a totally autonomous fly. Compared to manned aircraft, UAVs are often preferred for missions that are too "dull, dirty or dangerous" for humans. The UAVs were created for military use and nowadays most of them are still being used in this field. However, in the last years the use of the UAV in civil activity is increasing considerably. The UAVs can be classified taking into account different criteria. This classification can be consulted in Annex A.

The UAV global military market is dominated by the United States and Israel. The US held a 60% military-market share in 2006 and operated 9000 UAVs in 2014. From 1985 to 2014 exported drones came predomintantly from Israel (60,7%) and the United States (23,9%). The countries that imported most UAVs were The United Kingdom (33,9%) amd India(13,2%) [5]. However, in this project the military applications will be left apart, and the focus will be civil applications. The civil applications of the UAV are increased day by day. Some of them can be consulted also in Annex A.

The leading civil UAV companies are currently DJI (Chinese), Parror (French) and 3DRobotics (US). UAV companies are also emerging in developing nations such as India, where a few early stage startups have received support and funding [6]. Considering the trends and statistics until now of the UAV market, the civil UAV market is estimated to climb steeply, and might surpass the military drone segment. In the following graph is possible to appreciate the growth of both, civil and military, UAV markets.

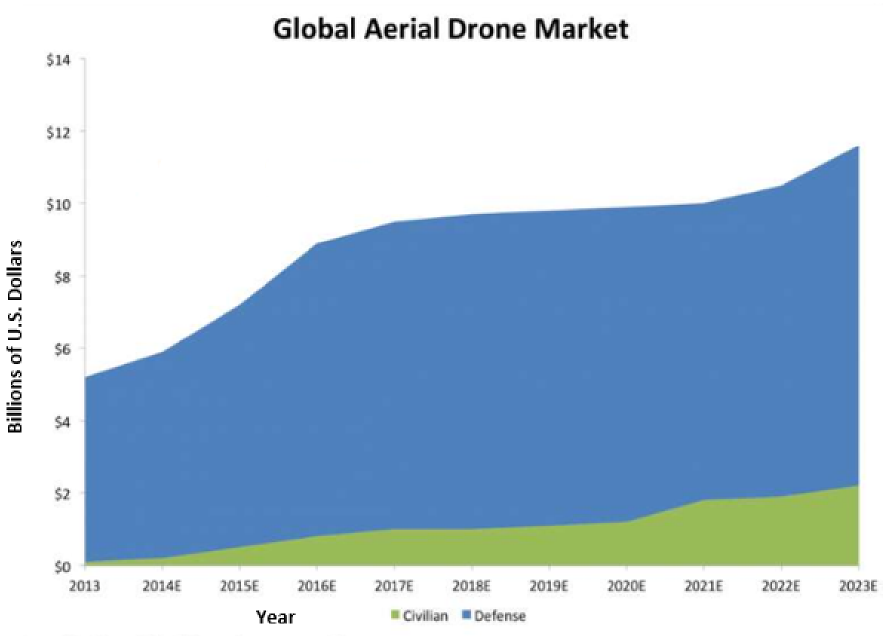


Figure 5.0.1: Aerial Drone Market. Image extracted from [1]

It can be said that the UAV civilian market is rising rapidly, with a wide variety of applications where the one that will be studied in this project can be fitted.

6 UAV design

The UAV needed for this project can not be a commercial one. There are two main reasons for that. First of all, a commercial UAV's software is not open-source, so it would not be possible to modify it. Secondly, in this type of UAV the structure is closed, so it would be difficult to apply a system of generation and management of energy. Moreover, it is not clear that there are UAVs in the market with the capability of fulfilling the requirements of the project, but if they were, they would be expensive and still have the difficulties associated with its modification. For these reasons, the best choice is to choose separately the suitable parts for the UAV and assemble them according to the requirements presented in previous chapters. The design of the UAV will be done taking into account the explanation of UAV's parts shown in Annex B. To design the UAV properly, a flow chart has been developed and can be consulted in the following page. As it is shown, three iterations levels have been defined for the UAV design, which depend on the battery design (battery weight, in fact), electric compatibility between battery and motor, and total weight of the UAV, i.e., power needed for flying.

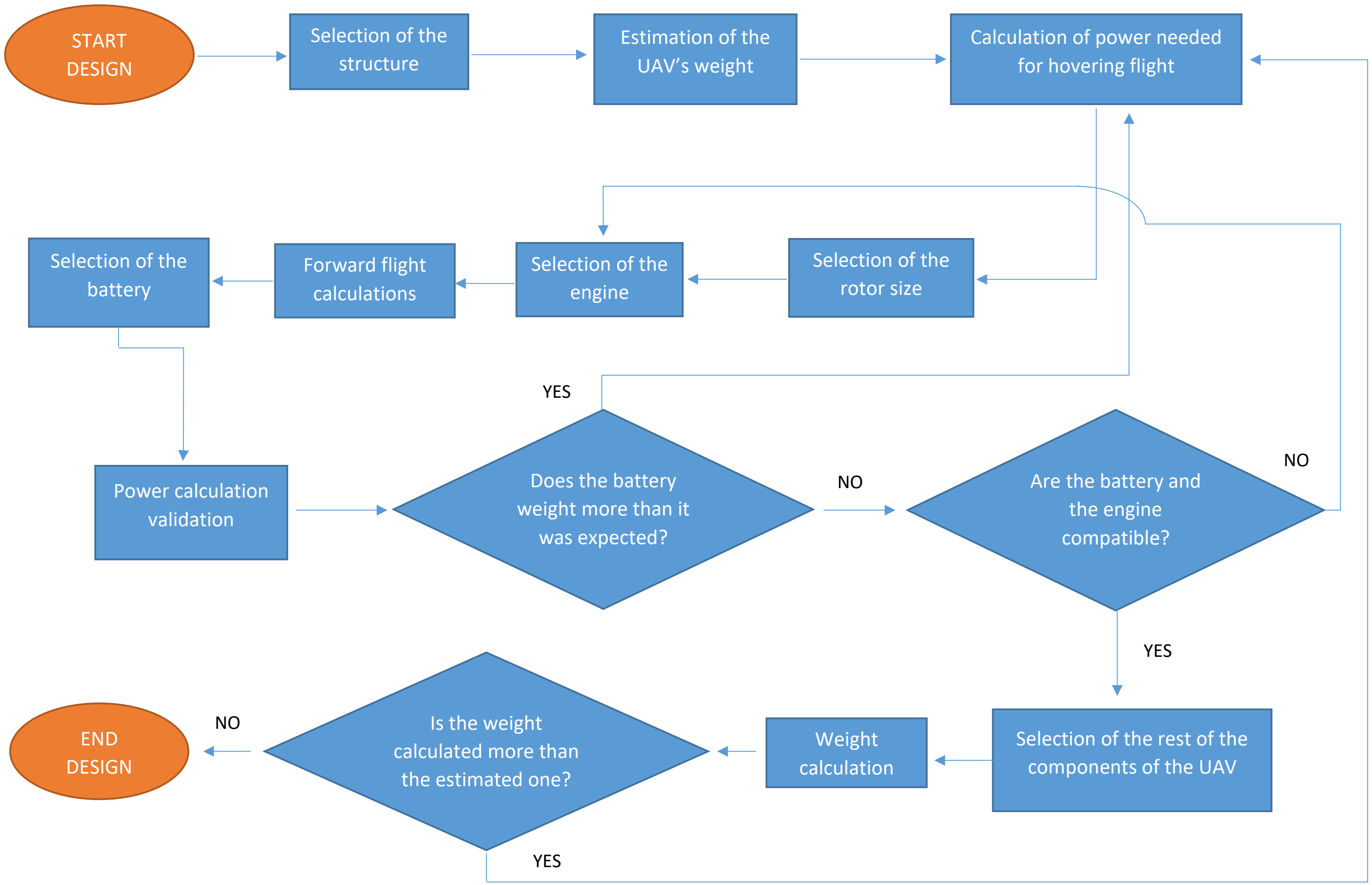


Figure 6.0.1: UAV Design flow chart

6.1 Frame

The information exposed in Annex B.1 will be used in order to choose which type of structure is most suitable for the UAV's mission. First of all, unfavourable frames will be discarded. These frames are:

- Y6
- Hexacopter
- Octocopter
- X8

They are discarded due to the fact that, although they are capable of carrying more weight and they possess redundant elements, their consumption is higher than in the remaining frames. The payload that will be carried in the mission of the UAV has a very low weight and the fact of not having redundant elements is not critical, because a communication between UAVs will be established in order to know whether one UAV has arrived to the target or not, so the other could replace it in case the first had failed in its mission.
The remaining frames are tricopter and quadcopter. The chosen structure is the quadcopter, because it can carry weight and it is more stable and less complex. It could be argued that the consumption of the quadcopter will be higher. However, this is not always true because although the tricopter has less arms, it can also have four rotors to compensate the gyroscopic effect.
A research on the market will be done with the aim of finding the available frames. The decision of what frame to use can not still be taken, because it will also depend on the selection of other components. In Annex C.1 most suitable frames found together with their main characteristics and the recommendations are shown.

6.2 Power and energy calculation

The power and energy calculation have been done. In this report only the main calculations and results are shown, the whole procedure can be consulted in Annex C.

6.2.1 Power for hovering and selection of the rotor size

As shown in Figure 6.0.1 an estimation of the weight is needed. This will be done by searching UAVs in the market with similar structure and looking at their component's weight. The results of the research are shown in Table 6.2.1.

Component	**Estimated weight(g)**
Structure	400
Flight controller+sensors	40
Engines+ESCs	250
Battery	650
Additional electronics	100
Payload	20
Total weight	**1430**

Table 6.2.1: Estimation of weights

Helicopter's aerodynamics will be applied in order to know the energy and power requirements. This theory can be consulted in [7], [8] and [9].
To calculate the power of the engines needed, the momentum theory for axial flight will be used. In hovering flight (there is no climbing or forward speed), the engines have to provide enough thrust to compensate the aircraft's weight, so the thrust per engine is the following one:

$$Thrust = \frac{1,43 \cdot 9,81}{4} = 3,51N \tag{6.2.1}$$

Using the mentioned theory, the ideal power per engine will be:

$$P = T \cdot \sqrt{\frac{T}{2\rho A}} \tag{6.2.2}$$

Where T is the thrust per engine, ρ the density of the air (sea level will be considered) and A is the are swept-out by the propeller of 1 engine. Here comes up the problem that the size of the propellers is still unknown. There are different types of propellers and they are named with two numbers, for example: 9x4,7. The first number gives the diameter in inches and the second one the pitch (incidence angle) of the blade. The surface and the thrust needed will be calculated considering different sizes of propellers, and then, the size of the rotor will be selected depending on the results obtained. Taking into account the structure's limitation, the propellers will be considered up to 10 inches.
Ideal power is calculated for different rotor's size, as can be consulted in Annex C.2. The result is relatively low due to the fact that in the momentum theory for hovering flight, parasitic power is not considered. Real power can be calculated using the figure of merit, that is:

$$FM = \frac{Pio}{Pexp} \tag{6.2.3}$$

Where Pio is the ideal power and Pexp is the real or experimental power. Obviously the FM is never one. On some documents is possible to found that in the most advanced helicopters de figure of merit is 0,8 [10]. However, the UAV studied here has not the same characteristics as helicopters, so it will have a different FM. It will be calculated using the blade element momentum theory. To use this theory the following data is needed:

- Rotation speed
- Drag coefficient
- Chord

Doing a research on the market of engines that could suit in the frames pre-selected, it is found that the rotation speed of most of them is of approximately 1000 rad/s, so this value will be used.
The drag coefficient is the one of the profile of the blade. It depends on the blade and its aerodynamics. Manufacturers of UAV propellers do not give this information, so estimation has to be done. A profile without curvature will be considered, as the NACA 0015. With this profile the drag coefficient can be obtained using the aerodynamic curves. The coefficient depend on the incidence angle, that can be extracted from the pitch of the blade. The more pitch it has, the more drag it has too. To design the UAV, highest pitch angle will be considered (worst situation in terms of parasitic power needed). The highest pitch value of propellers used for the kind of UAV studied is 6 inches.
The chord is not constant along the blade, it depends on the distance to the center. At the tip the chord is lower, to reduce the effect of tip vortex, and the maximum chord is located more or less at R/2. The propellers usually have a distribution like the one shown in Figure 6.2.1.

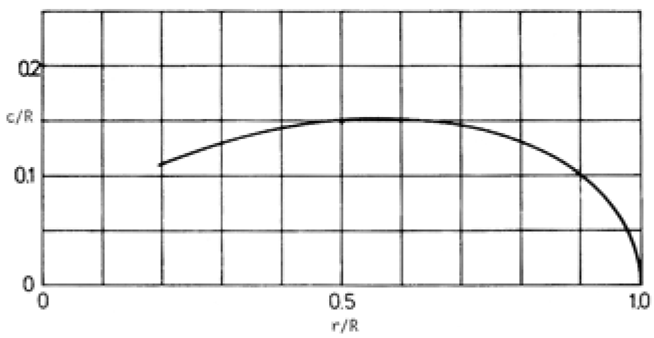


Figure 6.2.1: Chord distribution

To calculate the FM, the mean value of the chord is considered as 0,12R.
With the data and results obtained, is possible to calculate the real power needed for the UAV to flight in hovering mode.

D(inch)	Pi(W)	FM	Real power(W)
3	62,21	0,9768	63,69
4	46,66	0,9036	51,63
5	37,33	0,7661	48,71
6	31,11	0,5683	54,71
7	26,66	0,3948	67,47
8	23,33	0,5394	43,22
9	20,74	0,3662	56,581
10	18,66	0,2349	79,37

Table 6.2.2: Real power for hovering flight

As can be appreciated in Table 6.2.2, for a propeller of 8 inches, the consumption is lower than in any of the other cases. For this reason a propeller of 8 inch diameter (20,32 cm) will be used.

6.2.2 Engine selection

With the area of the rotor selected, is time to choose the engine. An OWA (Ordered Weighted Average) will be used to do so. The factors that will be taken into account are:

- Angular velocity: As it has been considered an angular velocity of 1000 rad/s, this factor will rate how close is the engine's angular velocity to the one predicted. That is to say: the engine that has an angular velocity closer to 1000rad/s will have a 5, and the engine that has an angular velocity more distanced to 1000 rad/s will have a 1. The weight of this factor will be 90.

- Power: The power has to be higher than 44W, as it is the power calculated. All the engines that don't achieve this value, will be automatically discharged. The other engines will be rated from 1, to the one with lowest power, until 5 to the one with maximum power. The weight of this factor will be 30.

- Weight: The less weight the better, so the engines will be rated from 1 to 5 from more weight to less weight. The weight of this factor will be 80.

- Cost: With cost happens the same as with weight, the less the better. The weight of this factor will be 40.

In Annex C.3 the results of the OWA are shown. The engine most suitable for this application is the 9192000199-0, which has the following properties:

Pmax(W)	Weight(g)	Ω (rad/s)	Cost(€)
99	48	1129	15

Table 6.2.3: Properties of the selected engine

6.2.3 Energy and power in forward flight

The next step according to the flow chart to design an UAV is the calculus of the energy and power needed for the battery in order to achieve the required range. There is something important that remains unknown: the forward speed of the UAV. The starting point for obtaining the power in forward flight is to do forces equilibrium. In a first approach, the rotor force that goes against the movement will be neglected. The equations are:

$$Tcos(\theta) = W \tag{6.2.4}$$

$$Tsin(\theta) = D = \frac{1}{2}\rho V^2 SC_D \tag{6.2.5}$$

To calculate the power needed to fly, momentum theory can also be applied:

$$T = 2Vi\rho\pi R^2\sqrt{Vx^2 + (Vz + Vi)^2} \tag{6.2.6}$$

$$Pi = T(Vz + Vi) = 2Vi\rho\pi R^2(Vz + Vi)\sqrt{Vx^2 + (Vz + Vi)^2} \tag{6.2.7}$$

No climbing speed is considered, so $Vz = 0$ in both equations. With equations 6.2.4 and 6.2.5 thrust and forward speed can be calculated using different θ. Having this two values, with 6.2.6 and 6.2.7 is possible to calculate the power needed. The drag is needed to resolve the problem. In [11] a study of the influence of the electronics, engines, and so on in the drag of an UAV has been done in a wind-tunnel. The results obtained are useful for this project and can be appreciated in the Figure 6.2.2. Since the UAV studied in this project is similar to the 450 UAV, its drag coefficient will be used. The angles of attack studied will go from 2 to 30 degrees, so $C_D = 0,22$ can be considered.

The surface of reference is needed. It will be approximated as can be seen in Annex C.4.1. One third of the equivalent circumference surface (0,33 times the equivalent surface) will be considered as the reference surface. Most of the frames pre-selected have a diameter of 500mm, so the reference surface will be:

$$S = \frac{1}{3}\pi\left(\frac{0,5}{2}\right)^2 = 0,065m^2 \tag{6.2.8}$$

With all this data, the ideal power for forward flight is calculated. This power decreases as the forward speed increases. As the ideal power only depends on thrust and induced velocity, and looking at the equations used, this is an expected result. As it has been done when calculating

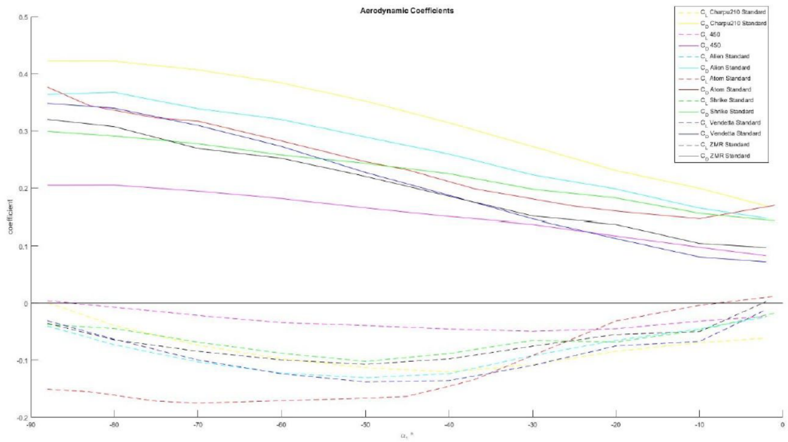


Figure 6.2.2: Drag coefficient of ready to fly UAVs. Extracted from [11]

the power in hovering flight, parasit power has to be taken into account. In this case the FM can not be applied because it is only useful for hovering flight. Using the Blade Element Theory with the Momentum Theory, real power can be calculated[1].

$$C_Q = \Big(\lambda_i + \frac{Vx}{\Omega R} sin(\theta)\Big) C_W + C_{Q0} + \frac{Vx}{\Omega R} cos(\theta) C_{H0} \tag{6.2.9}$$

Where:

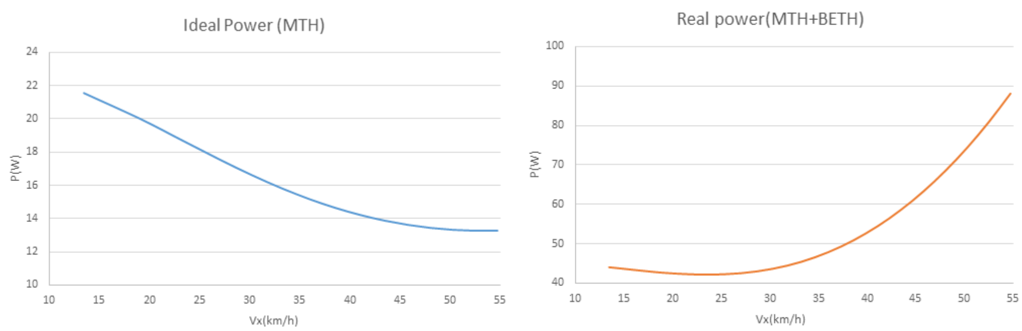
$$C_W \approx C_T \tag{6.2.10}$$

$$C_{H0} = C_T tan(\theta) \tag{6.2.11}$$

$$\lambda_i = \frac{Vi}{\Omega R} \tag{6.2.12}$$

And C_{Q0} is the coefficient calculated without taking into account the effects of the parasitic drag and H.

The results obtained are can be appreciated in Figure 6.2.3.



(a) Ideal

(b) Real

Figure 6.2.3: Power for forward flight.

[1]More information about the equations and simplifications exposed can be found in [8]

The power consumption increases exponentially for velocities higher than 35km/h. Applying a security factor of 10% in order to know the amount of power the engines need to provide, the result can be appreciated in Figure 6.2.4.

Taking into account the engine's maximum power, the maximum forward speed will be between 50 and 55 km/h. Considering a mean velocity of 30 km/h, at which the consumption is in its lowest region, the energy needed for the whole UAV to fly through the specified range can be calculated.

At 30 km/h, each of the rotors consume 50W. The range is 20km so:

$$\frac{20}{30} = 0,67h = 40min \tag{6.2.13}$$

The total energy needed for the UAV is shown in Table 6.2.4.

Velocity (km/h)	30
Range (km)	20
Fly time(h)	0,667
Engine consumption (W)	50
Total engine consumptions(W)	200
Flight controller and sensors (W)	2
Total consumption(W)	202
Energy needed (Wh)	134,67

Table 6.2.4: Total energy needed

Figure 6.2.4: Power needed per engine to mantain a forward flight

6.3 Battery selection

As shown in Figure 6.0.1, the battery has to be chosen. To do so two facts has to be taken into account: the energy and the maximum power. The maximum power the battery has to provide is the maximum that the engines can require. This value is 396 W. After doing a research on the market, some suitable batteries are found. The OWA method will be used again to decide which one of the batteries is the most suitable. The factors and their weights are:

- Power: 20
- Weight: 40
- Cost: 10

Result of the OWA can be consulted in Annex C.5. According to the OWA, the selected battery is the multistar high capacity battery, with reference 912700005-0. The characteristics of this battery are:

Energy (Wh)	Maximum power (W)	Weight(g)
177.6	3552	1025

Table 6.3.1: 912700005-0 characteristics

This battery weights more than it was expected, so a recalculation has to be done in order to know if the battery is capable or not to maintain the selected velocity the specified range with the increase of weight. As the process is the same that the one it has been already done, only the results are shown:

Total weight(g)	1766
Thrust per engine (N)	4,33
Real power for hovering(W)	51,8W
Energy needed for forward flight(Wh)	174

Table 6.3.2: Recalculation of the energy needed

The battery selected is capable of providing this amount of energy, so it is a battery suitable for the application explained in this project. The engine is also suitable with the increase of weight and the rotor size does not change. However, something is still to be confirmed, is the battery compatible with the engine? The battery has an output voltage of 22,5V while the engine has an input voltage of 11V. The intensity will be regulated with the Electronic Speed Controllers (ESC), but to regulate the voltage an additional converter is needed, and this means and additional weight. Looking back at the pre-selected engines, one of them has an input voltage of 22.5V, suitable for the 6S battery. The angular velocity of the engine is also suitable and the maximum power is almost double the one of the first engine. However, as it has more voltage and less intensity, its weight is not twice the weight of the first engine, so it is a good option. The specifications of the selected engine are the following ones:

Pmax(W)	Weight(g)	Ω(rad/s)	Cost(€)
180	63	1084	18,55

Table 6.3.3: Specifications of engine 9392000045-0

Now that the engine has changed, it has to be checked if the battery is capable of providing the amount of power that can require the engines. The maximum power that can require all the engines is 540W, and the maximum power that the battery can give is 3552W, so there is no problem with the maximum power to provide.

6.4 Power calculation validation

In order to validate the results and to see if the hovering and forward flight calculations done are correct, a research on the market will be done. The focus will be the battery, the autonomy and the maximum forward speed of existent UAV, together with the functions they do. All of the UAV considered will be quadcopters, for it would make no sense to consider other configurations in energy and power comparison.

UAV	Characteristics	Weight (g)	Battery (Wh)	Max speed (km/h)
Parrot BEVO P2 FPV	Camera + gimbal	500	30	56,7
DJI Phantom 4	Camera + gimbal	1380	81	72
Splash Drone Mariner II	Water-proof UAV + Camera	1150	62	—
DJI Mavic Pro	Camera + gimbal	740	44	64
DJI Inspire 1	Movable landing gear + Camera +gimbal	2935	130	50
Syma X5C X5C-1 Explorer	Camera	916	2	—
DJI Phantom 3 Professional	Camera + gimbal	1280	68	57,6

Table 6.4.1: Energy of the batteries of UAVs in the market with their speed and autonomy

Weight (g)	Battery (Wh)	Forward flight speed (km/h)
1766	177,6	30

Table 6.4.2: Characteristics of the designed UAV.

First of all, is easy to see that the maximum speed calculated of the UAVs in the market is quite higher than the mean speed considered for the designed UAV. Moreover, the maximum speed of these UAVs is equal to the one calculated before changing the engine, so the approximation of the speed is correct. The UAV designed in this project, in contrast with all the UAVs that have been exposed in the previous table, does not have a camera. This means that the consumption of the UAVs exposed in the table is higher than the one of the UAV that is being designed in this project, because they need to have a camera to take pictures or filming and a system to maintain this camera stable (gimbal). Moreover, they also have a communication system always working and sending the images, as WiFi in the case of the Parrot UAVs. This devices consume a lot of power, so the power of the UAV designed here will be less than the one of the UAVs of the table. The power of the battery selected for the designed engine is more, so is the autonomy. Taking as an example the DJI Inspire 1, which is the one that has a battery similar to the one selected, it weights 1kg more and still have 20 minutes of autonomy with camera and gimbal system. The results obtained during this study of energy and power calculated seem to agree with what is already on the market, so the results and the method used will be considered as correct, and the selection of the rest of components can be carried out.

6.5 Propeller

As it has been said, a propeller of 8 inch is the most suitable for the application. The energy and the power have been calculated with a 6 inch pitch, so if possible, a 8x6 propeller will be obtained.
A good option has been found in the market. Is important to take into account that propellers are CW or CCW. For a quadcopter, 2 CW and 2 CCW propellers are needed. In the following table the product is exposed:

Brand	Reference	Product	Cost(€)
Aerostar	074000131	2 CCW 8x6 Prop	1,59
Aerostar	074000207	2 CW 8x6 Prop	2,31

Table 6.5.1: Chosen propellers

6.6 Control and measurement electronics

In this section the control and measurement electronics are defined. First of all, the tasks that need to be done by this system are stated:

- **Point 1:** The energy that has been used and the energy that is being used in a specified moment has to be obtained.
- **Point 2:** The coordinates of the UAV need to be known. This coordinates include latitude, longitude and height from the ground. Orientation of the UAV is also needed. This coordinates will also go to a microprocessor in order to know the path followed.
- **Point 3:** : In order to know if the UAV has achieved the target or not, a communications system is needed. The information that the communication system will send will be stated also by a controller.
- **Point 4:** The flight will be autonomous, so Waypoint flight mode needs to be accepted by the flight controller and the information necessary to do this type of flight needs to be obtained.
- **Point 5:** The speed of the rotors has to be stated depending on the position of the UAV and the path it has to follow.

- **Point 6:** The voltage of the battery has to be converted in order to supply energy both to the flight controller and the engines.
- **Point 7:** The software of the flight controller needs to be open source in order to allow modifications.

The scheme of the control and measurement electronics is shown in Figure 6.6.1.

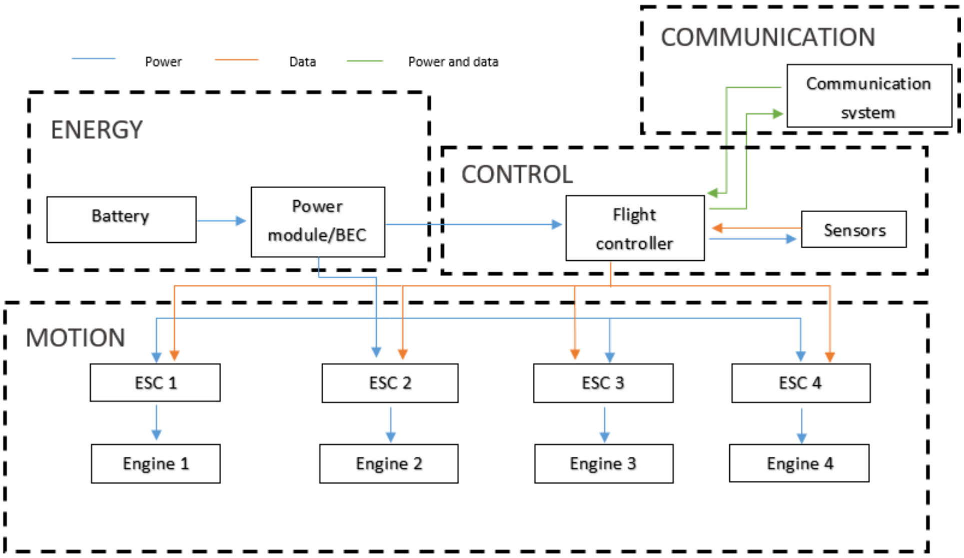


Figure 6.6.1: Control and measurement in the UAV

In the following sections the elements that appear in the scheme will be specified.

6.6.1 ESC

The ESC will accomplish part of Point 5. The flight controller will send a signal to the ESC in order to increase or decrease the amount of intensity given to the engines. The ESC has to be capable of providing at least the maximum intensity the engine can require. However, is important for the intensity that can provide the ESC to be higher than the maximum intensity of the engine. This is due to the fact that if the ESC is working at its maximum, it will overheat, causing a loss of energy. In this project one of the objectives is the optimization of energy onboard the UAV, so the losses of energy should be avoided. The selected engine has a maximum intensity of 8A. The manufacturer recommends the use of ESC of 20A, so this amount of amperage will be selected if possible. An OPTO ESC (optocoupled) does not have Battery Eliminator Circuit (BEC), so it would be suitable because having four BECs is unnecessary. In the selection of the ESC, it is also important that they can work with a battery like the selected one, that is: 6S LiPo. After a research on the market, an ESC that fulfil all the requirements is found. The specifications are shown in the following table.

Reference	Imax(A)	Input voltage(V)	OPTO	Weight(g)	Cost(€)
261000023-0	20	4-6S	Yes	23	9,23

Table 6.6.1: ESC specifications

6.6.2 Flight controller

The flight controller has to accept the waypoint flight mode and the possibility to include sensors and communications systems. It has also to be open source so if a change is needed (for example, to incorporate the communication system), it could be done by accessing to the code. Doing a research on the possible softwares to use, Mission Planner [12] is found. It belongs to the Ardupilot community and works as a ground station, i.e. works as a remote computer with which the mission can be monitored and the path can be selected using waypoints navigation. Information can be send to and from the UAV using this software, so it is suitable for this project. Mission Planner is compatible with the flight of planes, multi-rotors and autonomous terrestrial vehicles. It accepts a wide range of sensors, and can monitor de SoC of the battery if voltage and intensity measures are provided. The software is also open source and could be modified if needed. A flight controller compatible with this software will be chosen. There are, widely, four types of flight controllers that can support Mission Planner:

- Pixhawk: General use
- Pixracer: Small frames.
- PX4: UAV very small and fast.
- NAVIO+ or Erle-Brain: Vision-related applications.

Pixhawk results the most suitable one because it is for general use. It can support medium configurations like the one of the designed UAV and allows to add sensors easily like GPS, barometer, etc. Pixhawk is a brand, and in the market other flight controllers that perform its functions can be found under another name. In Annex C.6.1, the specifications of two flight controllers, 3DR Pixhawk 32bit Autopilot and HKPilot 32 are shown. If these specifications are consulted, it can be seen that both flight controllers have exactly the same microprocessor and have included the same sensors. The only difference is that the Pixhawk is the original brand while the HKPilot 32 is a "clon". In some occasions problems related with the uploading of the firmware in the HKPilot 32 has been reported. However, in all the cases it has been solved and currently HKPilot 32 is totally compatible with Mission Planner and other softwares product of Ardupilot [13]. For the exposed reasons, HKPilot 32 will be selected.

Figure 6.6.2: HKPilot 32

6.6.3 Sensors

6.6.3.1 Waypoing navigation

As stated in Point 4, it is desired that the UAV performs an autonomous flight, that can be done using waypoints navigation. To perform a waypoints navigation the sensors needed are: gyroscope, accelerometer, compass, barometer and GPS.
The selected flight controller has gyroscope, accelerometer, magnetometer, and barometer, so a GPS/Compass is still needed. There are devices that include both sensors. Looking for light-weight reliable systems, the following item is found, which is suitable for the application:

Reference	Product	Weight(g)	Cost(€
9387000040-0	Quanum LEA-6H GPS with Compass	38	65,65

Table 6.6.2: GPS/Compass specifications

Figure 6.6.3: Quanum LEA-6H GPS/Compass

6.6.3.2 Measurement of height

Not Barometer either GPS give the height of the UAV. Barometer measures the pressure of the air and, using the ISA (International Standard Atmosphere), altitude can be calculated. This result, however, is different at the same height with different climatic conditions. GPS

Figure 6.6.4: Maxbotix I2C sensor

calculate the position (including height) of the object using trigonometry with the time the signal is transferring to satellites and back. This measure has an error of approximately 2 meters (depending on the GPS), so is not precise enough. Several options that can solve this problem will be further studied. These options are:

- Infrared:This type of sensor consist on an IR LED and a photodiode.
- Lidar: With a lidar sensor, distance is measured using laser light.
- Sonar: In this case no light is used. Instead of that, sonar uses sound propagation to detect objects.

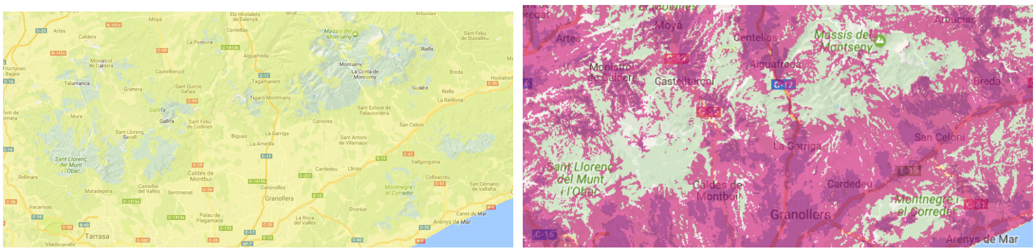
As it has been said, the information of this sensors will go directly to the flight controller, so it could know the distance to the ground and effectuate safely the landing of the UAV. In Annex C.6.2 the characteristics of a number of promising sensors that has been designed thinking in an UAV application (meaning they are light weight), is shown.
It has not been possible to find data about weight, accuracy and resolution of the IR-LOCK, so they will be discharged as weight, for example, is a very important factor to take into account. There are other two sensors that are also discharged: TeraRanger One Rangefinder and LIDAR-lite. The reason to do that is that TeraRanger One needs to be powered through and special adapter (TeraRanger I2C Adapter) between 12 and 16 V, whereas the flight controller can provide 5V and the battery 22,2V, so a DC/DC converter will be needed, increasing thus the complexity and weight of the system. Regarding LIDAR-lite, something similar happens: additional devices are needed such as an external BEC and three capacitors [14].
To choose between the other ones, the distance at which the sensors has to detect the ground needs to be specified. GPS has an error of approximately 2 meters, which means that the UAV being at 2 meters could be measuring a distance from 0 to 4 meters. This is a risk because the engines could stop at this distances causing a crash of the vehicle. Then, the sensor needs to detect the ground at two meters in order to counteract the error of the GPS. The minimum range provided by the sensors is 7 meters, which is a good range for the application in issue. To choose between the remaining sensors, the important factors are weight and cost. Then, the selected sensor is the Maxbotix I2C Sonar, because it has de lowest weight and cost. Its resolution is 1 cm, suitable for the landing of the UAV.

6.6.4 Communications system

Two things are important regarding the communication system. Firstly, the communication system will need to be controlled by the flight controller or an external micro. For the task stated, messages will only be send when needed (time interval specified in the flight controller or the external micro), so the communication system will not communicate continuously because it would mean an unnecessary power consumption. Secondly, the range the communication system will need to cover is of 10 km, an elevated range in comparison with most civilian UAVs. The types of communication systems that will be studied to cover this requirements are GSM and Satellite communication.

6.6.4.1 GSM

First of all, the functionality of this system has to be assured. GSM is a standard developed by the ETSI (European Telecommunications Standards Institute) to describe the protocols for second-generation digital cellular networks [15]. To be capable of sending or receiving information via GSM a connexion with an antenna of the communication operator has to be established. The location of the antennas depend on the operator and are mainly focused on providing coverage to urban areas. For this reason, a research on the grade of coverage in mountainous regions will be done. Coverage maps are search, and the result for two different operators is shown in Figure 6.6.5.



(a) Orange. Image extracted from [16]

(b) Yoigo. Image extracted from [17]

Figure 6.6.5: GSM coverage.

In the Figures, two mountainous regions close to Barcelona are shown: *Sant LLorenç del Munt I l'Obac* and *Massís del Montseny*. As it can be easily appreciated, with both operators the coverage is really poor and the communication via GSM can't be assured, so this communication system is not suitable for the mission studied in this project.

6.6.4.2 Satellite

The other possibility to communicate the UAV is to use Satcom[2]. Nowadays, research is being done in order to achieve real time communications with UAV using Satcom. The aim of this type of research is to improve Satcom used in civilian UAV, as in military UAV it

[2] Satellite communications are usually called Satcom

Figure 6.6.6: RockBLOCK Mk2

is the normal communication system. Military UAVs use governmental satellites to carry out communication. However, due to the increase in the number of UAV and the amount of information they recollect, these satellites do not have enough bandwidth and thus, commercial satellite companies are starting to supply service to military UAV opening the possibility also to civilian UAV. More interesting information can be found at [18] [19] and [20].
After doing a research Iridium is found. Iridium is a satellite constellation aimed to provide voice and data coverage to satellite phones over the Earth's surface. It is composed by 66 active satellite that orbit at 781 km (LEO) [21]. A British developer called Rock Seven Mobile has create a relatively low cost and light weight transceiver though to be used with Arduino [22]. This transceiver is called RockBLOCK Mk2 and uses the Iridium 9602 satellite modem. As all Satcom, the use of this device includes an initial cost and a monthly cost due to the service of information exchange with the Iridium satellite network [23] [24]. The specifications and power consumption of this module can be found in Annex C.7.

6.6.4.3 Decision

Two communication systems has been studied: GSM and Satcom. GSM has result in an unsuitable communication system because of its poor coverage in the working are of this project. In contrast, Satcom can be easily integrated in the UAV. It is compatible with the flight controller used because it can provide the power RockBLOCK needs and the weight is relatively low to be implemented onboard the vehicle.

6.6.5 Power module/BEC

The BEC, as explained in Annex B.2.3, is usually a part of the ESC. The ESC selected are optocoupled and do not have BEC, so is time to investigate if we need an external BEC for the correct performance of the system or not. The BEC is used to supply power to the flight controller, it is a DC/DC converter that changes the voltage and intensity of the battery into the necessary input for the flight controller. The input of the flight controller and the sensors is 5V and the intensity 2A or less. Then, a converter is needed. There is a power module designed specifically to work with the HKPilot 32 and the compatible sensors. This power module has different versions, depending on the input. The battery is 6S (22,5V), so a power module that can deal with a range including 22,5V as an input will be suitable in this case. Here the specifications of the power module found are shown:

Reference	Product	Vmax input(V)	Imax input(A)	Cost(€)
387000052-0	HKpilot 10s power module	45	90	19,75

Table 6.6.3: Power module specifications

Figure 6.6.7: HKPilot 10s power module

This module, apart from doing the DC/DC conversion, provides measures of intensity and voltage of the battery. This information is transmitted to the flight controller and the remaining energy in the battery can be obtained.

6.7 Frame accesories

6.7.1 Battery support

Any of the frames pre-selected incorporate a proper and suitable support for the battery, where it can be safely added without possibility of failing and causing damage to the UAV or the battery itself. For this reason, a battery support will be designed in order to manufacture it by using a 3D printer. This support will be added to the frame using the available holes in it or creating new ones if needed. As it will be printed in 3D, considerations about its shape has to be taken into account. For example, no corbels or extremely thin walls can be manufactured satisfactorily. It will be created using software SolidWorks and its sizes will be fixed when the frame and the battery are definitely selected. Final support drawings will be available at Drawings document. An image of the preliminary battery support can be seen in Figure 6.7.1.

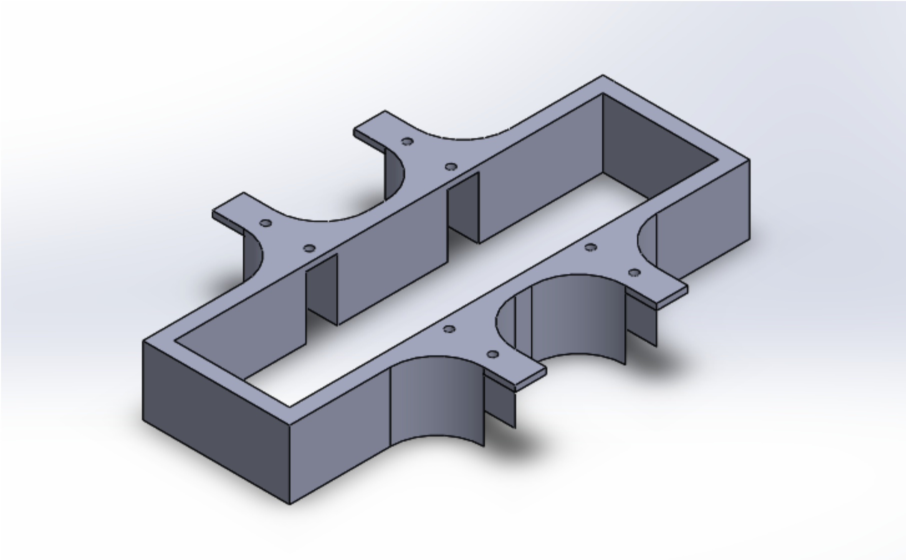


Figure 6.7.1: Isometric view of the battery support design.

6.7.2 Communication system support

The frames are not designed to carry a communication system like the one choosen. A plastic case will be elaborated to do so. Same as the battery support, the final sizes will be fixed when the frame is selected. The drawings will be available at Drawings document.

6.8 Recompilation of selected components

Here is time to state that all the components have been selected except the frame. Some of them where pre-selected at the beginning in order to have some restrictions regarding the size of the other components. Due to problems with availability of frames and compatibility, the only structure suitable for the project is the S500. It counts with a landing gear that absorbs the impacts and include a power board to connect the battery and the ESCs. In the following table, each selected component is defined with its ID, weight and cost.

Figure 6.8.1: S500 frame

Component	Weight(g)	Cost(€)
Frame	405	20,40
Motors	4x63=252	4x18,55=74,2
Propellers	—	2x1,69=3,38
ESC	4x23=92	4x8,56=34,24
Battery	956	77,18
Fligh controller	33,1	120,62
Power module	-	19,75
GPS/Compass	38	65,65
Sonar sensor	5,9	38
RockBLOCK Mk2	76	230
Frame accesories	20	-

Table 6.8.1: Components selected

Total weight	1878g
Total cost	683,42€

Table 6.8.2: Total weight and cost of the UAV

The total weight is higher than the predicted one, so according to Figure 6.0.1, the engine and the battery need to be calculated again. To do so, the same steps as the explained in Section 6.2 will be followed. In the following table, the estimation of weights is shown again, now knowing the one of the UAV and part of the additional electronics (Satcom module and Sonar sensor). An additional electronics weight will also be added in case a PV system is added or another microcontroller is needed to manage the communication system. An increment in the weight of the battery will also be added, because the calculated battery is probably not enough, so a larger battery will be needed.

Component	Estimated weight(g)
UAV and electronics	1878
Increment of battery	400
Additional electronics	20
Payload	20
Total weight	**2318**

Table 6.8.3: Re-estimation of weights

Now the results are shown in the following table:

Thrust per engine (N)	5,63
Real power for hovering (W)	67,66
Energy needed(Wh)	254,67

Table 6.8.4: Recalculation of the energy needed II

The engine is still suitable but a larger battery is needed. Searching in the market, the following options are available:

Ref	Energy(Wh)	Pmax(W)	Weight(g)	Cost(€)
T 10 6S	222	11100	1440	199
T 12 6S	266,4	7992	1575	209
DP10000XP20-6S	222	4440	1260	175
DP10000XP15-6S	222	3330	1240	155
DP12000XP15-6S	266,4	3996	1395	195
TA-15C-1200-6S1P	266,4	7992	1640	239

Table 6.8.5: Possible larger batteries

The only battery that fulfil the requirements of energy and weight is the DP12000XP15-6S. The maximum power that can be required by the engines is 720W, that can be provided by the battery.

6.9 Conclusion

The results obtained have been exposed. Several iterations have been needed to obtain the optimal design of the UAV. The most difficult part of it has been the estimation of weights. It is very difficult to predict the weight of an UAV for a 20 km of flight, because this type of UAV is not the one that is usually sold and therefore the components are quite different to the ones a standard UAV has. This is due to more than one thing. First of all, the battery is larger than it was though, and adds almost 1 kg to the first predicted weight. Secondly, the weight of some components that are not present in other UAV were difficult to approximate. For example, UAVs usually operate in regions where 2G coverage is available, although most of them use short-range telemetry. The fact of adding a Satcom module increases the weight 80 grams and the price 200€. Nonetheless, with the battery selected, together with the other components, the range fixed in the requirements can be obtained.

7 System of renewable energy generation

This chapter deals with the fact of including a system of generation of green energy in order to increase the range in good climatic conditions. The range needed can be already covered by the elements selected, but the fact of increasing it without damaging the performance of the UAV is studied and, if it is a good option, put into practice.
In order to generate energy on board the UAV, photovoltaics where chosen in the first chapter of the project. The available space in the UAV to implement the energy generation system has to be specified. Then, a research on the market of the available technology is done looking for high-efficiency, light and cheap solar cells that employ the technologies studied selected.The most suitable system is selected using an OWA if needed. Last of all, an evaluation of its utility is be done.

7.1 Photovoltaic systems

First of all, the basics of photovoltaic technology and the current state of it in the market is now explained. Photovoltaics (from now on called PV) cover the conversion of light intro electricity using semiconducting materials that exhibit the photovoltaic effect. A typical photovoltaic system employs solar panels, each comprising a number of solar cells, which generate electrical power. PV don't generate pollution and the conversion of energy takes place without any moving part. The problem of PV is their low efficiency, and the fact that the power output is affected by weather conditions such as the amount of dust and water vapour in the air or the amount of cloud cover. Advances in technology and an increasing manufacturing scale have reduced the cost, increasing also the reliability and the efficiency of PV [25]. More than 100 countries use this technology which is the third renewable energy source in terms of globally capacity. In 2014 the installed PV capacity in the world increased to 177 GW, which is 2% of the global electricity demand [26]. Not only is PV technology growing exponentially, its cost is also declining abruptly. This makes PV a great option to consider when obtaining green energy. In Figure 7.1.1 Swanson's law is represented together with experimental points. Swanson's law states that solar cell prices fall 20% for every doubling of industry capacity [27].

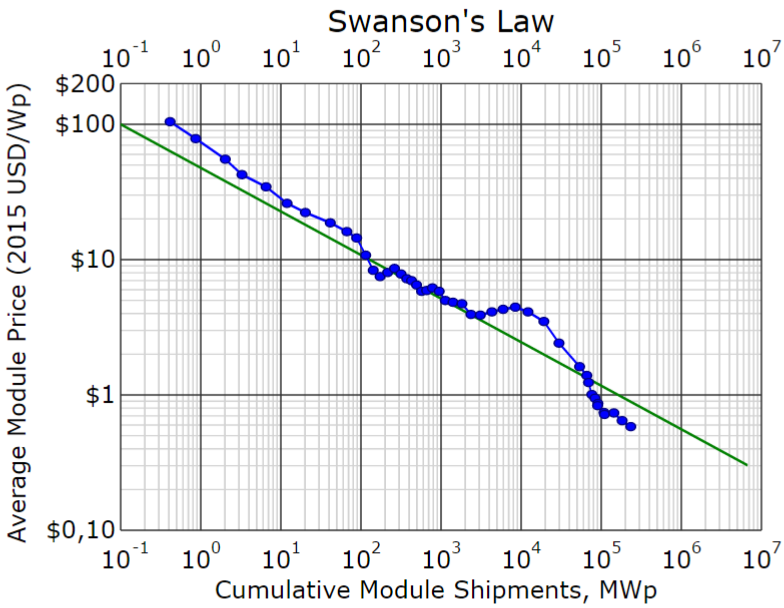


Figure 7.1.1: Swanson's law

As it has already been said, PV power generation employs solar panels composed by solar cells. Materials presently used for PV include [28]:

- Monocrystalline silicon
- Polycrystalline silicon
- Amorphous silicon
- Cadmium telluride
- Copper iridium gallium selenide

The main developments of solar cells focus on the efficiency of them. Most of solar cells available in the market (made of monocrystallyne silicon) have an efficiency of more or less 16%. However, in 2014 three companies broke the record of 25,6% for a silicon solar cell and in 2015 a 4-junction GaInP/GaAs/GaInAsP/GaInAs solar cell achieved a new laboratory record efficiency of 46,1% [29]. In Figure 7.1.2 a time line with the solar cell with best efficiencies obtained in laboratory conditions is shown.

Solar cells can be made of only one single layer (single-junction) or can be made using multiple physical configurations (multi-junctions). Multi-junctions cells are useful because more than one material can be used, so various absorptions in different spectres take place. Solar cells can also be classified into first, second and third generation. The cells that are currently available in the market are silicon and thin film cells. More information about this types of solar cells can be found in Annex D.1.

Usually thin film solar cells can weight twice than conventional solar cells. For this reason

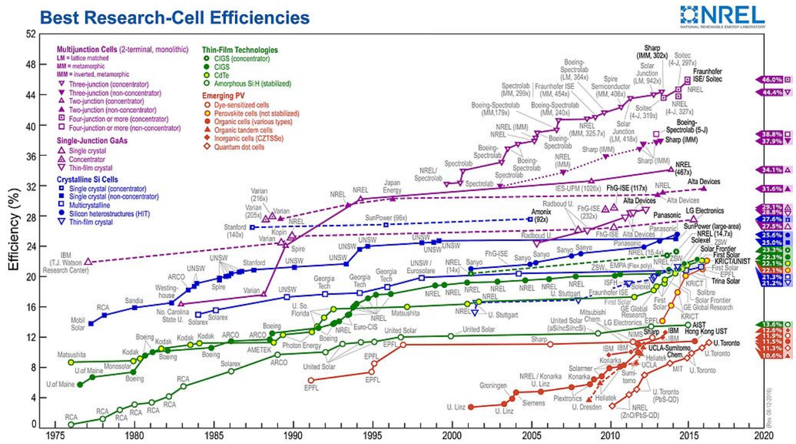


Figure 7.1.2: Solar cells with best efficiencies. Image extracted from the National Renewable Energy Laboratory

it might seem good to choose conventional solar cells. However, there is one manufacturing process that can make thin film solar cells lighter: thin film flexible solar cells. The type of thin-film solar cell most extended and the one that is used to elaborate flexible solar cells is amorphous silicon (a-Si), which is expected to provide low-cost PV modules [30]. However, there are also flexible cells made of CIGS which claims to have higher efficiency than the solar cells made of amorphous silicon [31]. The flexibility is obtained by using a flexible substrate (a polymer). The main advantage in using thin-film flexible solar cells is their light weight and the possibility to adapt the solar panel to the UAV's structure. The main drawback of this technology is that the efficiency of the cells in the market is still lower than in the case of crystalline silicon cells, and they are also more expensive.

The type of solar cells that will be considered for the UAV are crystalline silicon solar cells and thin film flexible solar cells. Although this decision has been made, a research on the market of the exploration avenues of the PV systems has been done in order to see future possibilities. This research can be consulted at Annex D.2.

7.2 Available space in the UAV for placing the solar cells

The available surface to install the PV system is need. In the case of thin film flexible solar cells are used, there is the possibility of placing them surrounding the UAV, increasing then the available surface. The problem here is that the surface will not be directly exposed to the sun, and the rays inclination would decrease the efficiency of the cell. The parts of the solar cell without direct incidence of the sun would have a small contribution in comparison with solar cells with direct exposure. For this reason only a flat surface will be considered.

Two possibilities can be considered when placing the solar panel in the UAV. Both of them can be consulted in Annex D.3. Here, only the solution is shown.

The solar panel will be placed above the electronics but not under the rotor area to avoid

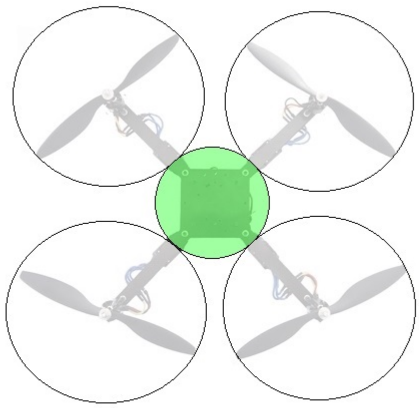


Figure 7.2.1: Location of the PV system, 2

aerodynamic drawbacks. The available surface is, then:

$$A = 0,0314 m^2 \tag{7.2.1}$$

The result is shown in an illustrative manner in Figure 7.2.1. This configuration will be considered when choosing the solar cells or solar panels to install in the UAV. Solar cells are not usually circular, but they are neither a perfect square. For this reason, the surface will be considered as a reference, and solar cells with similar surface will be search. Then, after knowing if they are suitable or not, the attention will go to the x and y dimensions to know if they can fit in the UAV or if there are combinations between more than one cells are possible.

7.3 Research and selection of solar cells in the market

A research on solar panels and whether they are useful or not for the UAV will be done. The focus will be on small solar panels, because most of the commercially available solar panels are designed for home applications which means that they are big and heavy. There are quite a few types of small solar panels for this type of application, but only crystalline silicon and thin film flexible solar cells will be considered. After doing the research[1], some filters will be applied in order to obtain the solar cells that could fit in the UAV. The filters are:

- The PV system has to weight less than 20 grams. This is due to the estimated weight done during the calculation of energy and power of the UAV.
- The surface has to be lower than 0,0314 m^2.

[1]In Annex D.4 tables with the solar cells with its characteristics can be found, together with the process that is explained in this section

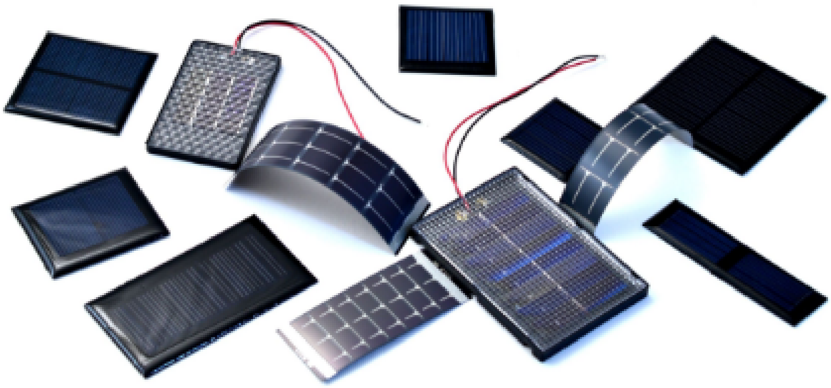


Figure 7.3.1: Different small solar panels for stand-alone systems. Image extracted from [32]

- x and y dimensions of the panel.

After applying the filters, some remaining solar cells resulted to be much smaller than the space that can be filled, so possible combinations of more than one cell of the same type will be considered if the resulting weight is less than 20 grams.
After applying this process, several solar cells have been pre selected. To choose between an OWA will be used. In Table 7.3.1 the factors, that will be rated between 1 and 5, are described.

Factor	Description	Weight
Power	The higher the power the better, so the solar panels that can provide higher power will be the 5 and the one that can provide less power will be the 1.	9
Weight	Weight is an important feature about the generation of energy system. Although all the systems of generation that will be evaluated accomplish the requirement to weigh less than 100 grams, 5 will be given to the solar panel with less weight and 1 to the heaviest one.	9
Surface	All the solar cells can fit in the area pre-established. However, it would be better if they could occupy less. For this reason, 5 will go to the smallest solar panel and 1 to the bigger.	4
Cost	This factor is also important. The cheaper the better.	6

Table 7.3.1: OWA for the decision between different solar cells

The results are of the OWA are shown in Annex D.4. The most suitable energy generation system is the option number 19, which characteristics are shown in Table 7.3.2.

Type of solar cell	Mono crystalline silicon
Efficiency (%)	20,4
Power (W)	5
Vout (V)	0,6
Iout (A)	8,33
X dimension (m)	0,156
Y dimension (m)	0,156
Weight (g)	20
Cost (€)	2

Table 7.3.2: Solar cell selected characteristics

Is possible to see that after the study, a crystalline silicon cell has been chosen instead of a thin film flexible solar cell, this is mainly due to the fact that its efficiency on the cells available in the market is higher. They are also cheaper and the difference in weight is not wide enough to choose thin film flexible cells instead of crystalline silicon cells. If this study is carried on again in the future, with the developments that are being studied by the scientific community in the market, this decision may be different that the one done now.

7.4 Usefulness study

Now that the solar cell has been selected, it has to be said if it is really useful or not to the UAV given the mission studied in this project.
First of all, the power needed to lift the solar cell is calculated in order to compare it with the power the solar cell can supply. Only the weight of the solar cell, without the energy management electronics, will be considered. Using the same method as the one explained in 6.2, the results are in Table 7.4.1.

Solar cell weight(g)	20
Weight per engine (N)	0,049
Ideal power (W)	0,038
Figure of merit	0,7
Real power (W)	0,055

Table 7.4.1: Power needed to lift the solar cell

It can be appreciated that the solar cell can provide 90 times the power needed to lift it if no electronics are considering, so is possible to put it without decreasing the available energy for the flight. However, this fact does not assure that the solar cell is useful. Considering that the autonomy of the UAV is 40 minutes and that climatic conditions are optimum, the amount of power extracted from the PV would be:

$$5 \cdot 0,67 = 3,35Wh \tag{7.4.1}$$

As the total energy that the UAV needs for its flight is of 254,6 Wh, the contribution of the solar cell represents 1,316% of the total energy. In other words, the solar cell could increase the autonomy of the UAV in only 0,4 minutes, so the energy supplied by the solar cell compared to the one needed is insignificant.

It may seem that as the solar cell does not suppose a lost of energy there is no drawback in including it. However, this would be a wrong assumption. It has to be taken into account that the solar cell needs to be accompanied by an energy management system which would allow the output of the cell to charge the battery. This system would have a weight and a complexity, so including the cell would involve an increase in the aerodynamic drag (a lot of elements located above the UAV), an increase in the design complexity and in the cost of the project.

Talking about the energy management system, for the cells output and the battery considered, the elements that would be needed are:

- Boost converter
- Battery management system

The battery considered is a 6S Lipo, which means that its voltage is 22,2 V and needs to be charged at approximately 25,2 V. That means that the boost would need to convert 0,6 V into 25,2 V, and this is a problem. The duty cycle needed to achieve this result is:

$$D = \frac{V_{out} - V_{in}}{V_{out}} = 0,98 \tag{7.4.2}$$

This duty cycle is extremely large and not supported by a lot of controllers. One alternative would be to apply a cascaded boost converter, that increases complexity and weight of the system. Moreover, the conversion will take place with losses and the output intensity would be very small in comparison with the battery capacity (12Ah). The battery management system is a system that controls the charge of the battery and assures that the voltage of all the cells are the same. Doing a research on the market, the cost and weight of the elements explained are shown in Table 7.4.2.

Element	**Characteristics**	**Weight (g)**	**Cost (€)**
Battery charger	$V_{in} = 5V$; $V_{out} = 22 - 28V$	200	95
Boost converter	$V_{in,min} = 0,3V$; $V_{out} = 5V$	100	40
BMS	6S, 10A discharge rate	10	10

Table 7.4.2: Example of energy management elements

Is easy to appreciate that the cost and weight is incremented almost without benefits.

7.5 Conclusions

The option of including a solar cell in the UAV is discharged. There are several reasons to do that, which are explained in the following lines.
First of all, is important to point out that the calculations shown in the previous section have been done with optimum conditions that are usually achieved in controlled laboratory atmospheres. For this reason the real power that could be obtained with the solar cell would be much lower than the nominal power used, becoming a more insignificant value. This power is not useful for the performance of the UAV that has been designed in this project, so there are no real benefits of including the solar cell. The power could be increased by increasing the available surface in the UAV to place the solar cell. However, the relationship between the surface of the UAV's frame and the power that could be obtained from the UAV is not linear due to, amongs other, the increase of weight and size of other components.
Secondly, as has been explained in the usefulness study, in this case the power obtained from the PV would not benefit the UAV and the complexity and cost of it would be increased.
To sum up, it could be said that the fundamental problems in adding a PV system to the UAV are the available surface, the low efficiency and the circuitry needed to make the solar cell functional.
Although now the conclusion of this chapter have been these, if this study and calculations are done again in some years time, the result is sensitive to change. Third generation system of solar cells is a promising technology that has not been commercialised yet. They claim to be light and high efficiency cells, but there are still a lot of improvements to be done. Thin film flexible solar cells can also be a good option. They have been considered in the selection of the solar cell but, as nowadays their efficiency is low in comparison with crystalline silicon cells, they have not been selected. With future developments their performance will probably improve and maybe they could get beyond conventional cells.

8 Algorithms

In this chapter the explanation and flow charts of the algorithms elaborated are shown. As said during the specification of requirements and technologies to fulfil them, creation of a communication system, database and tracking and flight trajectory optimization programs are needed. Also, a flight analysis algorithm will be developed to monitor the performance of the UAV during this project. The language and tools used to carry out this part have been:

- MATLAB language
- MATLAB software
- C++ language
- Arduino IDE
- Python language
- Notepad++ source code editor
- Command prompt or cmd.exe

8.1 Communication system

As said in Section 6.6.4, the communication system that will be used is a module of Satcom. The Satcom RockBLOCK Mk2 is not directly compatible with the flight controller used. RockBLOCK Mk2 supports only SBD (short-burst data) communication while the telemetry ports of the flight controller use MAVLink (micro aerial vehicle link) protocol to transmit information. There are two ways to make RockBLOCK Mk2 work with the UAV:

- Modifying the program of the flight controller. The program of this code has 700000 lines, and its telemetry library would need to be changed in order to allow the flight controller to output different types of telemetry data using the telemetry ports. The type of telemetry data would need to be changed in order to be send using the Iridium constellation and new features related with the Iridium modem would need to be implemented.

- Adding a microprocessor to receive the data of the flight controller, manipulate and send it using the Iridium constellation and vice versa. This microprocessor would act as a bridge between the flight controller and the Satcom module.

Due to the size and complexity of the program of the flight controller, the second possibility is the one selected to make RockBLOCK Mk2 compatible with the flight controller. Moreover, the implementation of an on board computer would facilitate further future improvements of the UAV being in charge of path optimization, for example. The controller to be implemented will be an Arduino, as it is the one recommended by the RockBLOCK manufacturers and its features are suitable for the UAV. In the following image the paths that the communication follows are shown. It can be seen that a conversation is carried out between the Arduino and the flight controller of the UAV, done using serial communication. Arduino stores the interesting information and, when it is time, sends it to the Satcom module using AT commands. The Satcom module sends it to the Iridium constellation, which is in charge to connect to Internet and send the message using IMAP protocol (e-mail).

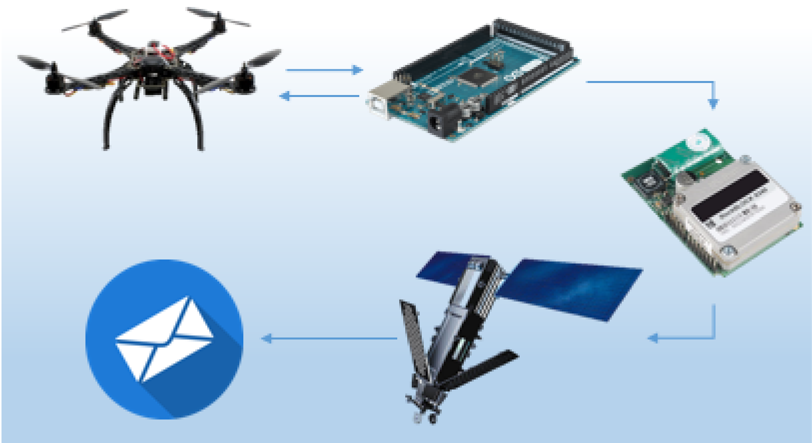


Figure 8.1.1: Communications scheme

In order to create the algorithm, a brief explanation about Iridium and MAVLink specifications is done.

8.1.1 Iridium

As said previously, RockBLOCK Mk2 allows SBD connectivity to the Iridium satellite. The information exposed in this section has been extracted from the Iridium library for Arduino [33], the RockBLOCK developer guide [34] and the Iridium 9602 SBD Transceiver developer guide [35].
Iridium can be controlled by data terminal equipment capable of sending standard AT commands via serial interface. This interface is always in one of three possible modes:

- Command mode: AT commands can be entered to control.
- SBD data mode: Transmission of binary or text SBD messages to the DTE.

- SBD session mode: SBD session with the Iridium network.

Iridium has two buffers to store the messages, depending if they are incoming or outgoing messages:

- MO buffer: Outgoing messages that will be sent through the Iridium constellation.
- MT buffer: Incoming messages received from the Iridium constellation.

The data transfer between the Iridium and the Arduino has to be stated to 19200 bits per second. The process to send and receive messages from and to the Iridium constellation is the following one:

1. Check the strength of the signal: If the signal strength is poor, the Iridium antenna would probably have problem when transmitting data to or from the constellation. This checking can be done using the command AT+CSQ. This command will give a response between 0 and 5. If the response is lower than 2, the most probably thing to happen is not to be capable of sending or receiving the information.

2. Write the message that wants to be send in the MO buffer: To send a message, it has to be stored in the MO buffer. To do so, "AT+SBDWT=<text message>" will be used.

3. Initiate communication with the Iridium constellation: To be able to communicate with the Iridium constellation, a message transfer session has to be initiated. The command used will be AT+SBDI. With this command the session is initiated and, if there is a message in the MO buffer, it will be sent to the satellite. The response of this command can vary, giving for example the status of the MO buffer and of the MT buffer (whether a message has been received or not).

4. Read the received message: If a message has been received, the command AT+SBDRT should be used to read the message and store it if needed.

5. Clean buffers: After a message is written in the MO buffer, it will remain there after it is send through the constellation. The same happens with the MT buffer.

The data sent and received by and from the Iridium constellation is encoded in binary. The process explained is the one that will be applied to the elaborated code.

8.1.2 MAVLink

MAVLink is a protocol mostly used for the intercommunication of subsystems of small unmanned vehicle and for communication between the vehicle and a Ground Control Station. In the following lines only the information about the protocol of special interest for the project will be explained. The information shown about the protocol and its commands has been extracted and can be broaden in [36].
The MAVLink protocol does the communication by exchanging packets encoded in ASCII. The

conversion between binary and ASCII to communicate between MAVLink and Iridium will be done in the Arduino board implemented. The maximum size of a packet is of 263 bytes. This size is suitable to be transmitted through the Iridium constellation, because it admits up to 270 bytes for incoming messages and up to 340 bytes for outgoing messages. The frame has eight bytes overhead to describe the type of payload and allow security checks. The meaning of the bytes can be consulted in Annex E.1.

When the flight controller is connected to a system it starts sending heartbeat messages[1] to show that a system is present and responding. The flight controller would expect the ground control station to send also heartbeat messages in response. If these messages are not received after a certain amount of time, the flight controller would assume that the communication link is lost and would enter into a failsafe mode. Entering into this mode will lead to different situations depending on the cause of it and the configuration that has been made. The objective of this project is to allow the UAV to fly autonomously without the need of continuous communication with the radio or a control ground station. For this reason, the parameter FS_ THR_ ENABLE of the flight controller has to be set to "Enabled Continue with Mission in Auto Mode" and the parameter GCS_ Failsafe has to be set to Enabled_ continue_ in_ auto_ mode. Doing this configuration, the copter will not land when communication with radio or control ground station communication is lost and thus constant heartbeat messages sent from the ground control station are not needed.

When connecting the Arduino to the flight controller and after sending a heartbeat messages, the flight controllers starts to send information. The information that is interesting for this application is the position of the UAV and the state of the battery. The ID of these two messages and information about them can be found in Annex E.2.

After receiving this information from the flight controller in the Arduino board, it can be send through the Iridium constellation to the control ground station.

Other interesting commands of the MAVLink protocol to send and receive information can also be seen in Annex E.3.

8.1.3 Code flow chart

In the following page the flow chart of the code can be visualized. To see the entire code, please refer to Annex E.4.

[1] Heartbeat message has ID 0.

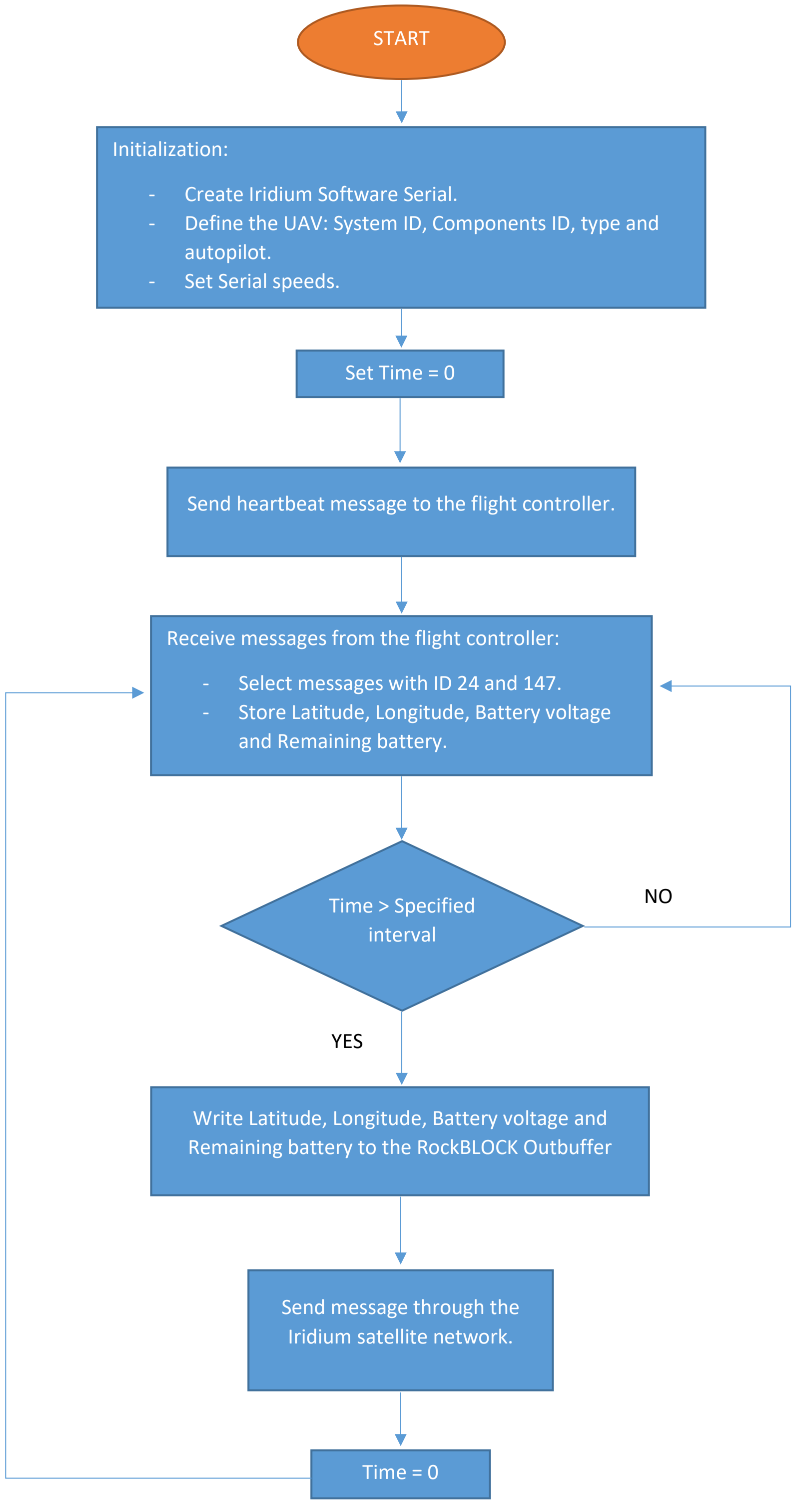


Figure 8.1.2: Communication system flow chart

8.2 Flight analysis algorithm

An analysis of the UAV flight is needed for several reasons. The most important one is the possibility to monitor the performance of the UAV and be aware of possible deviations with the optimal behaviour. In the frame of this project, this analysis is also needed for the comparison between the real and the theoretical power consumption of the UAV. For these reasons, an algorithm to do so is needed, and consequently, it has been developed. The data that has to be analysed is:

- GPS coordinates: With this data the correct following of the path is verified.
- Ground speed: In order to know the speed at which the UAV flights and assure that it follows the commands of the mission.
- Current consumption: To know the battery remaining and the consumption at different speeds this data is needed.

Data about the flight is collected every 200 ms by the flight controller and stored in the onboard dataflash memory, organized in packets. The data can be exported into a MATLAB format, so this program will be used to elaborate the code. The GPS coordinates are stored separately and can be open as a KML file. Regarding the other ones, the packets that have to be managed are the ones called CURRENT and NTUN. The organization of this packets can be consulted in Annex F.1.
In the following page a flow chart of the elaborated code is shown. To see the entire code please refer to Annex F.2.

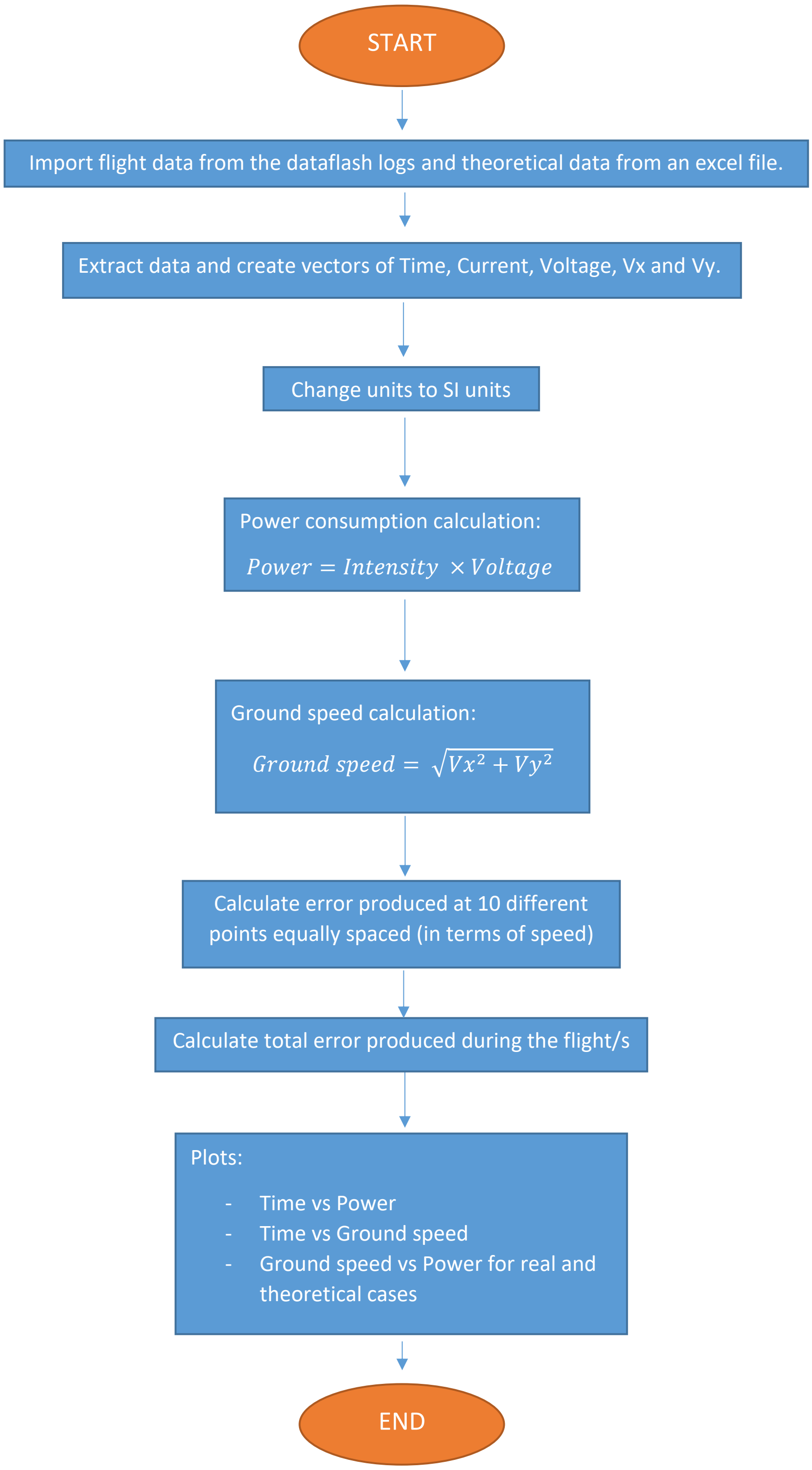


Figure 8.2.1: Flight analysis flow chart

8.3 UAV Tracking and Database

As the UAV will fly autonomously, a tracking system using the messages received from the Iridium constellation is needed. An algorithm will be created, with the aim of showing in a map the last/s position/s of the UAV sent from the communication system. To do so, Python language has been used as it is easy to implement and works satisfactorily with imap protocol, which is the protocol used in Gmail, where the Iridium messages are received.
The position of the UAV will be shown using a KML file, that can be opened with an Earth viewer software such as Google Earth. Besides the tracking of the position of the UAV, a database is also be created. This database stores the position of the UAV (latitude and longitude), the voltage of the battery and the remaining battery together with the day and time when the message was sent. With this database the behaviour of the UAV along time can be checked and maintenance can be done optimally. The database is a CSV [2] file, that can be opened with programs such as Excel. It is be composed by 6 columns, where the following data is be stored (data exposed from column more at the left until column more at the right):

- Day
- Hour (Zulu Time Zome)
- Latitude (°)
- Longitude (°)
- Battery voltage (V)
- Remaining voltage (%)

In the following page the flow chart of the code is shown. To see the entire code please refer to Annex G.

[2]comma separated value

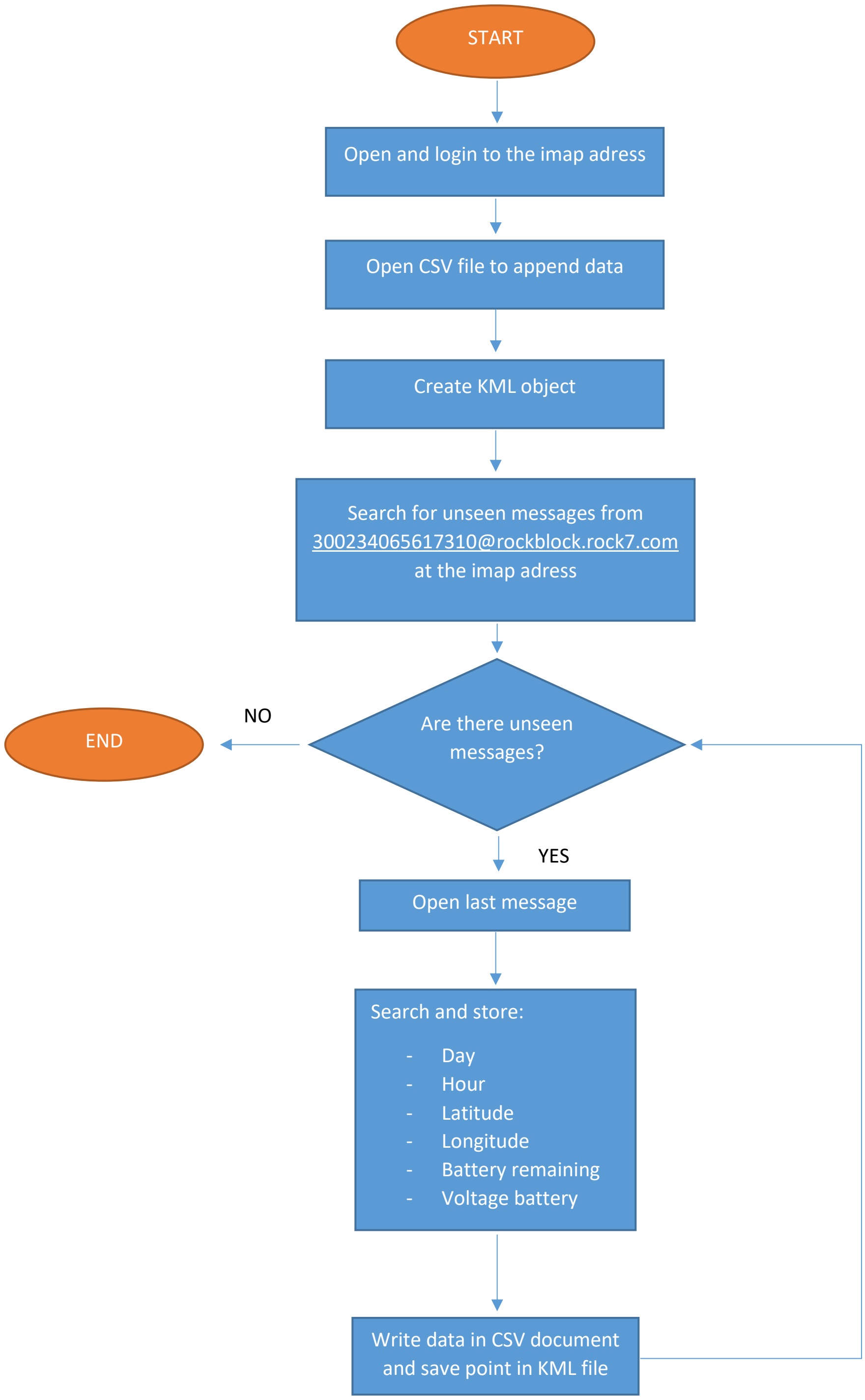


Figure 8.3.1: Data base flow chart

8.4 Flight trajectory

As the UAV is autonomous, a trajectory to be followed is needed. This path will be generated automatically by introducing the destination coordinates in a program and updated to the UAV using Mission Planner software, which connects to the UAV using MAVLink protocol. The file that has to be created with the program developed in this project is called Waypoint file. The format of this file and more information about the Waypoint Protocol can be found in reference [37]. Two different algorithms are developed to create the Waypoint file.

- First algorithm creates a straight flight between two points.
- Second algorithm takes into account power consumption regarding trajectory and optimizes it by selecting the trajectory with lowest consumption.

8.4.1 Straight flight

The objective of this algorithm is to calculate the distance between two points and the power consumption at an optimal speed. After doing so, it creates a Waypoint file that can be updated directly to the UAV. It is presented to the user as a program, that is to say, a GUI [3] of the algorithm has been created. MATLAB has been used to create this program. The needed inputs are:

- Home coordinates: They will be always the same as the UAV is supposed to stay in a station.
- Destination coordinates: Coordinates where the UAV needs to arrive.
- Consumption table: Table where the relationship between speed and power is shown. An excel file is used for this purpose.
- Available energy: Energy of the battery at full charge.

The only input that has to be introduced by the user will be the destination coordinates. To calculate the distance of the flight Harvesine formula will be used [38].
In the following page the flow chart can be consulted. To see the entire code please refer to Annex H.1.1.

[3] Guide User Interface

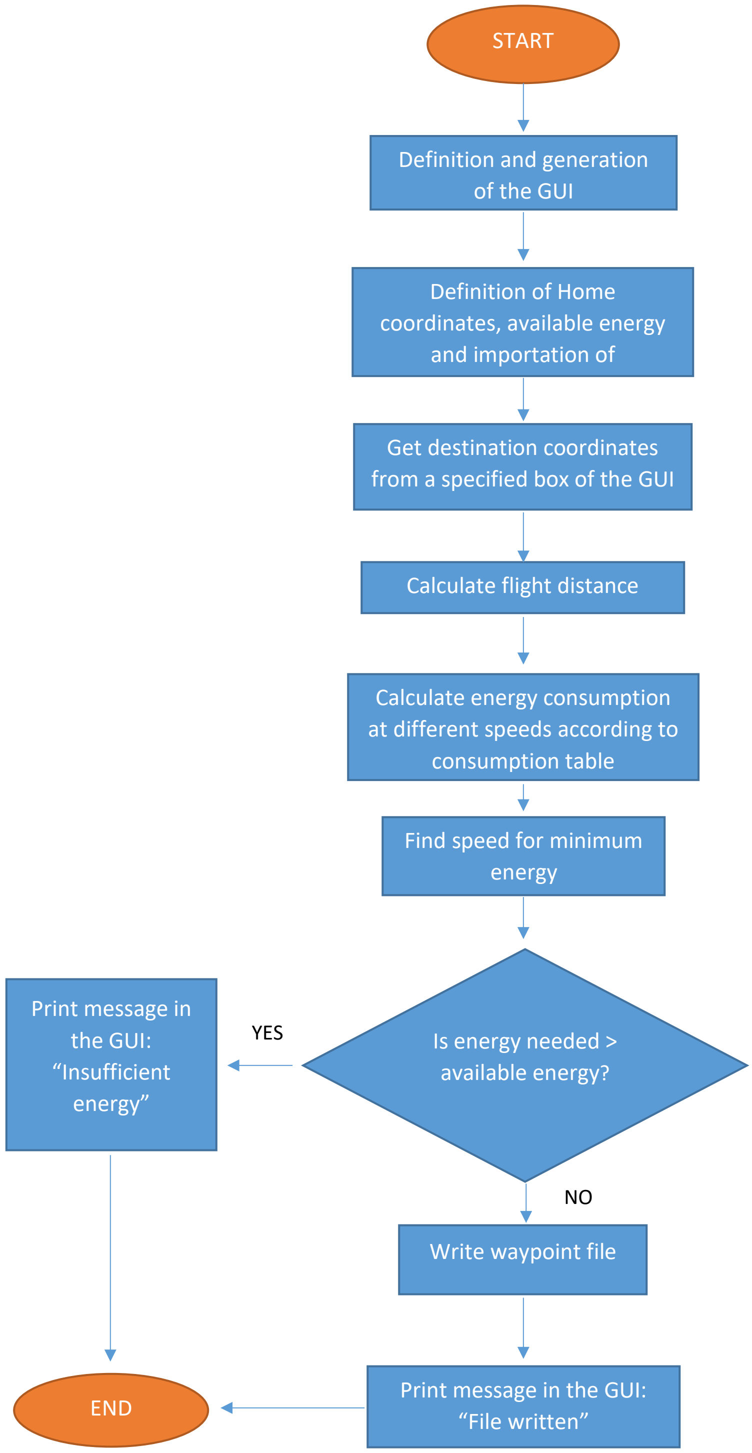
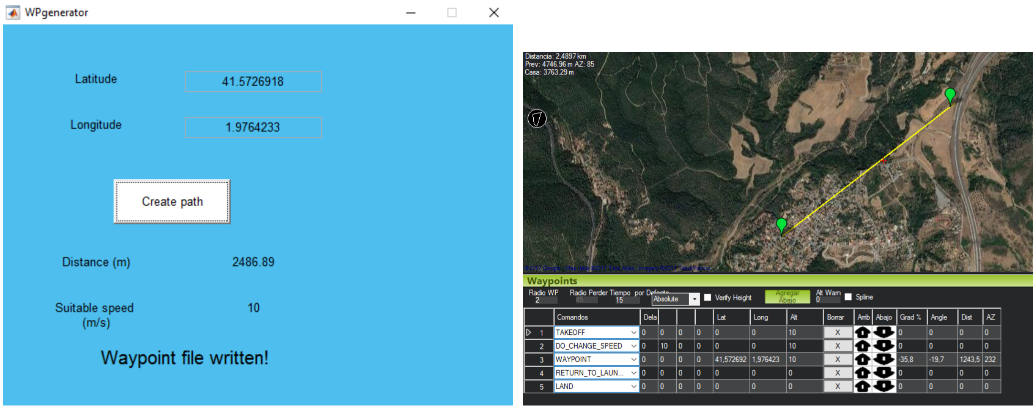


Figure 8.4.1: Straight flight flow chart

8.4.1.1 Results

In this subsection an example of the GUI and the trajectory obtained ready to be updated to the UAV is shown. To see all the states of the GUI see Annex H.1.2.



(a) Waypoint file generator GUI

(b) Waypoint file generated opened with Mission Planner

Figure 8.4.2: Result example

8.4.2 Trajectory optimization

In the previous section, the creation of a path to be followed by the UAV has been shown. Although a suitable speed in terms of power consumption has been chosen, the path is only optimal in conditions with no wind. However, this condition rarely happens and wind is an important fact that has to be taken into account. As can be seen in Thesis [39] the energy saving for an UAV optimizing the path according to the wind can be as high as 50%, for the airplane case. After reading the data exposed in the mentioned Thesis, the Dijkstra's algorithm is chosen to be implemented in the trajectory optimization. This algorithm is designed to find the minimum cost path between nodes in a graph where the edges have a specified weight. An example of the working procedure of this algorithm can be seen in Annex H.2.1. The algorithm can also be used to find the minimum cost between two specified nodes in a graph and the path to be followed to obtain this cost. More information about this algorithm can be consulted in [40].
Taking into account the information exposed an algorithm is created with the objective of creating and optimal path from the point of view of power consumed. To do so, the following inputs are needed:

- Home coordinates.
- Destination coordinates.
- Consumption table.
- Wind speed.

- Wind direction.

In this case a GUI is not created, as the procedure will be exactly the same as in the straight flight case. The Dijkstra's algorithm will be used as a function of the main code. This algorithm is already implemented in plenty of programming languages, so this function can be obtained from [41]. To use this function, the following inputs are needed and has to be calculated in the elaborated algorithm.

- Matrix A: NxN [4] adjacency matrix where A(I,J) is equal to 1 only if points I and J are connected.
- Matrix C: NxN cost matrix, where C(I,J) contains the value of the cost to move from point I to point J.
- SID: Identification of the starting node (node corresponding to the home coordinates).
- FID: Identification of the ending node (node corresponding to the destination coordinates).

The graph of nodes will be generated taking as a reference the parallels and meridians of the Earth. That is to say, a square will be created using the parallel and meridians of the home and destination nodes. The minimum side square distance is set to 2km so in the case the home and destination coordinates are located in the same latitude or longitude, the square will be created too. The distance between nodes will be of 0.0002 radians.
In this case all the nodes will be interconnected between them. To calculate the cost matrix, wind and ground speed vectors are used. The difference between them (vector's difference) give the relative speed of the UAV. The consumption at this speed can be known using the consumption table.
The output of the code is the waypoint file to be followed by the UAV. Plots are also be created in order to check its functionality.
After explaining the objectives and the needs of the algorithm, the flow chart is shown in the following page. The entire code can be consulted in Annex H.2.2.

[4] N is the number of nodes of the graph

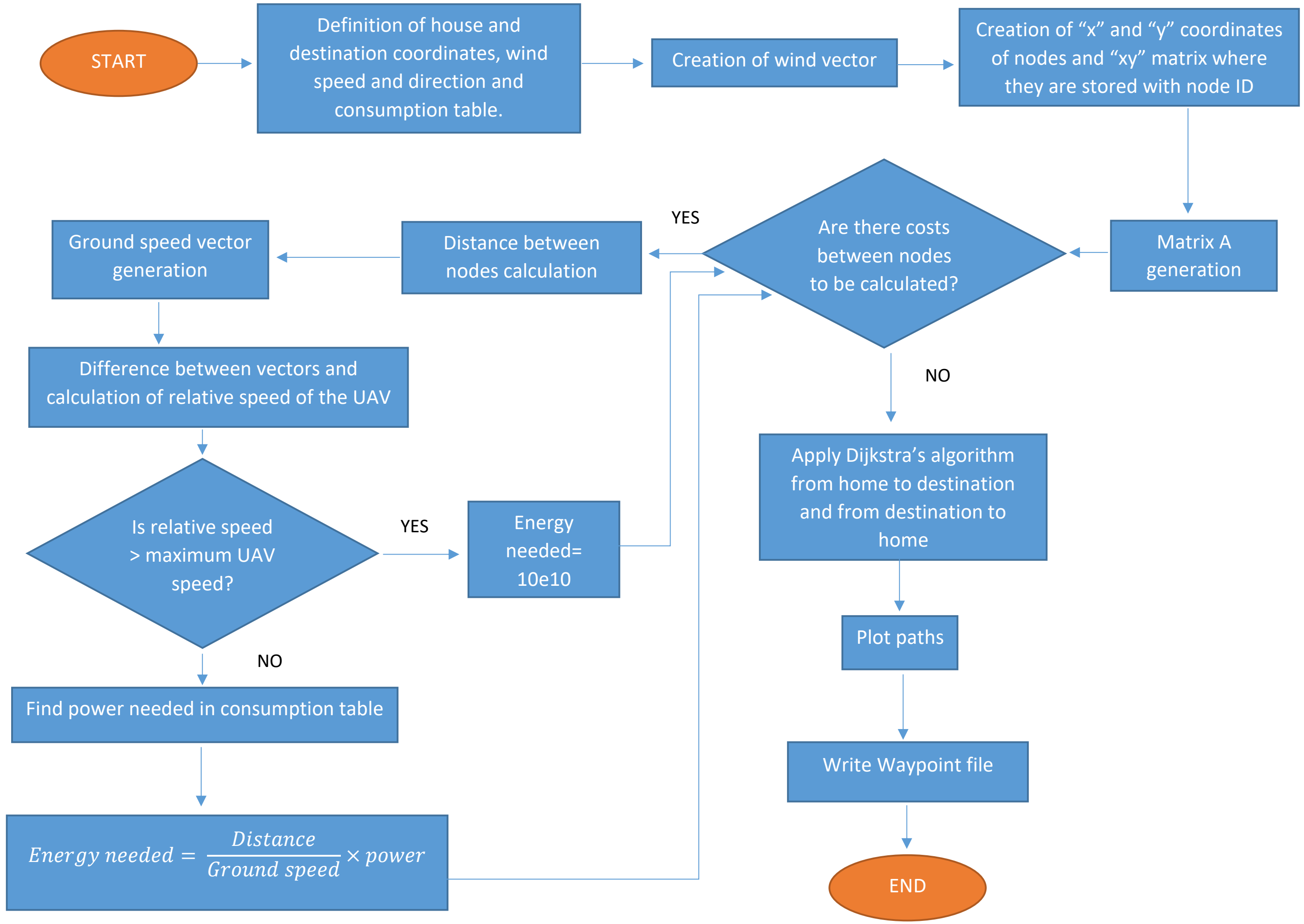


Figure 8.4.3: Trajectory optimization flow chart

8.4.2.1 Results

After developing the code and making some tests that can be consulted in Annex H.2.3, the optimal path is be calculated for real conditions between two aleatory points in Terrassa. According to AEMET [42] , the day 11/05/2017 the wind is of 4m/s in East direction. Introducing the data in the code, the result is shown in Figures 8.4.4 and 8.4.5. In this case the path from the home to the destination and from the destination to home is the same, with is something that does not happen always. The improvement in comparison with a straight line path in terms of energy is of 2.7 %.

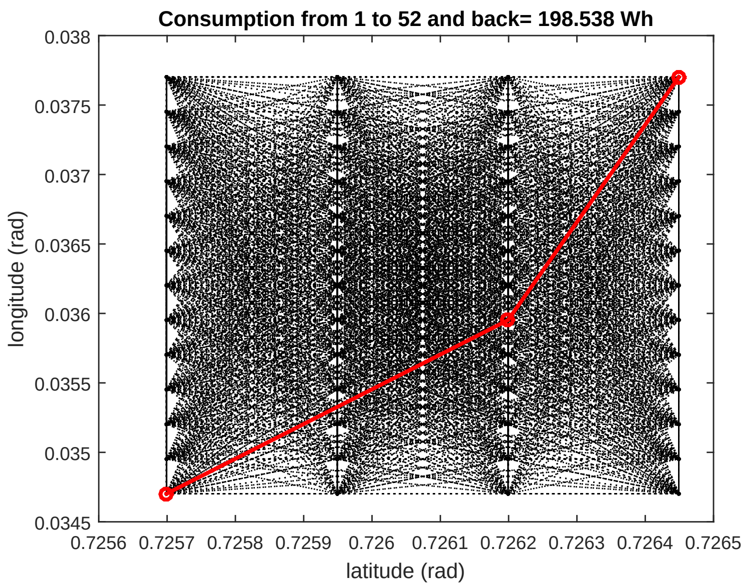


Figure 8.4.4: Optimal path between home and destination and back.

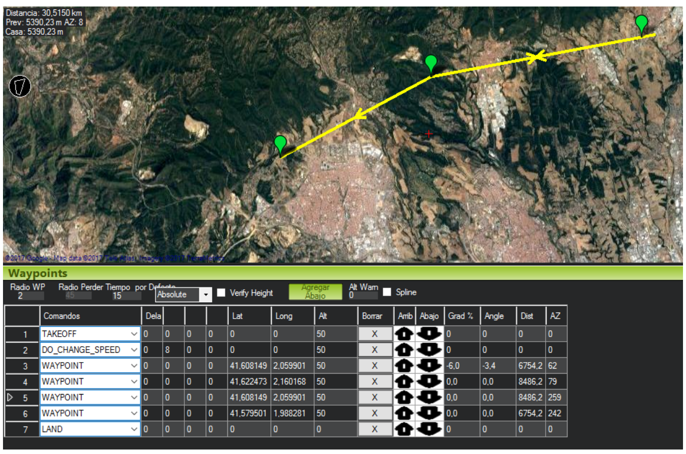


Figure 8.4.5: Waypoint file created by the program opened with Mission Planner.

Although in this case the improvement is small, the energy saving can be of almost 12%, as can be seen in Annex H.2.3.

9 Experimentation

9.1 Tests definition

A prototype has been build according to the design chapter of this project. As the design was for a family of UAVs that can change its range by changing the battery, the experimentation will be done with a medium-size battery. The battery and the power consumption of this UAV can be seen in Annex I.1. In Annexes I.2 and I.3 is also possible to see notes about the construction and the configuration/calibration of the UAV. Also, the electrical scheme of it can be seen in the Drawings document.
With the prototype built, the tests has to be specified. In summary the following tests have been performed:

- Electrical.
- Correct hardware operation.
- Correct software operation.

In the following lines the tests are defined.

9.1.1 Test 1: Electrical checking

First of all, a verification of the connexions is needed. This is done in two steps.

1. Visual inspection of the connexions. With this visual inspection the correct connexion of the different parts of the UAV is assured.
2. Continuity of the connections. This is done using a multimeter with continuity function. The aim of this step is to verify that there are no problems with the welding of the elements and that the connectors work properly.

9.1.2 Test 2: Operational checking

The operation of the different components has to be tested. The systems to check are:

- Engines: An engine test is carried out in order to assure its behaviour. This test has several steps and all of them have to be performed without propellers. To know the enumeration of the engines, refer to Figure 9.1.1.

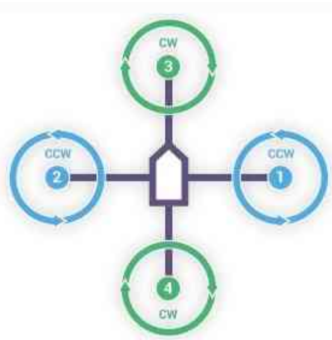


Figure 9.1.1: Enumeration of the motors. Image extracted from [2].

1. Verify spin direction of the engines.
2. Verify, in forward flight: acceleration of engine 4 and deceleration of engine 3.
3. Verify, when turning to the left: acceleration of engine 1 and deceleration of engine 2.
4. Verify, when turning to the right: acceleration of engine 2 and deceleration of engine 1.
5. Verify, in backward flight: acceleration of engine 3 and deceleration of engine 4.
6. Verify, in a stabilize mode, that when the position of the UAV is altered the response of the engines tend to put it back to the original position.

- GPS: The behaviour of the GPS is also checked. This is done by going outside with the UAV, connect the GPS and acquire the path it records.
- Sonar: The range of the sonar has to be the correct. To do it, the UAV is connected to the computer and the data of the status of the UAV is checked in order to know the range given by the sonar.

9.1.3 Test 3: Controlled flight in an open area

A controlled flight is done in order to assure the UAV can fly satisfactorily. The aim of this flight is to verify that the thrust of the engines can lift the UAV and that it is stable. During this tests the UAV is tied with a rope of different lengths depending on the progress and performance of it.

9.1.4 Test 4: Short range autonomous flights in an open area

These tests consist on several flights with two objectives. The first one is to test the possibility of the UAV to perform an autonomous flight and the second is to know the power consumed at different speeds. To do so the analysis algorithm is used after the flights. A comparison between the real power consumed and the theoretical one can be done in order to know the deviation produced during the design process. The flights to perform are:

- Hovering flight.
- Forward flight at 4 m/s.
- Forward flight at 6 m/s.
- Forward flight at 8 m/s.
- Forward flight at 10 m/s.
- Forward flight at 12 m/s.

These flights are done three times in three different days, and averaging of results is made to reduce the measurement errors. No more flights are done due to the limited time available. To change the speed the parameter WPNAV_ SPEED will be used. The commands and paths followed during all these flights can be consulted in Annex J.1. The climatic conditions of the flight days can also be consulted in the same Annex.

9.1.5 Test 5: Failsafe verification

An autonomous flight is performed, this time with a small quantity of energy available in the battery so the failsafe option should be used.

9.1.6 Test 6: Detection of crash verification

It has to be checked if the engines stop after a crash. For this reason a small crash is produced and the behaviour of the UAV checked.

9.1.7 Test 7: Communication system verification

The communication system has to be tested in the UAV in order to verify its functionality.

9.1.8 Test 8: Long range autonomous flight

As a final test, a long range autonomous flight is performed, including the communication system. As the space available to do the flight is limited by several facts such as the presence of roads, high-tension wires and the need of maintaining visual contact with the UAV due to the law, the path to follow is of 1,2 km with several stops and loiter in turns, so the endurance of the flight is approximately of 15 minutes.

9.2 Results

9.2.1 Test 1

The test shows that the connexions work satisfactorily.

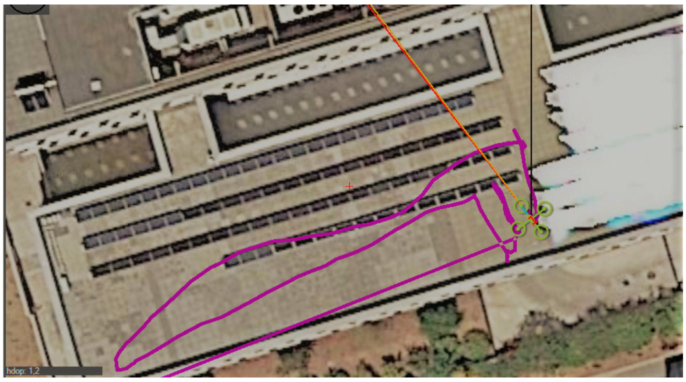


Figure 9.2.1: Path captured during the GPS test.

9.2.2 Test 2

Engines The engines work properly in all the steps followed during the process of this test.

GPS The GPS works properly in outside areas. The path recorded during this test can be seen in Figure 9.2.1.

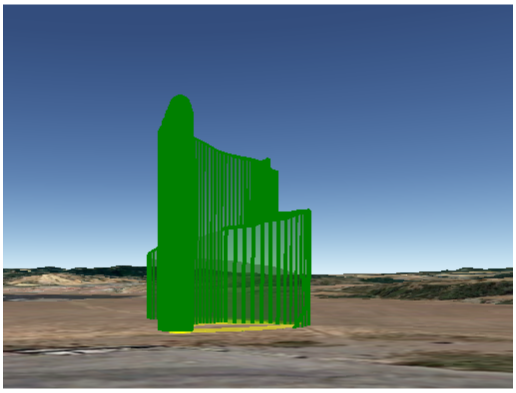
Sonar Connecting the UAV to the computer, the range captured by the sonar can be seen. Its behaviour is correct.

9.2.3 Test 3

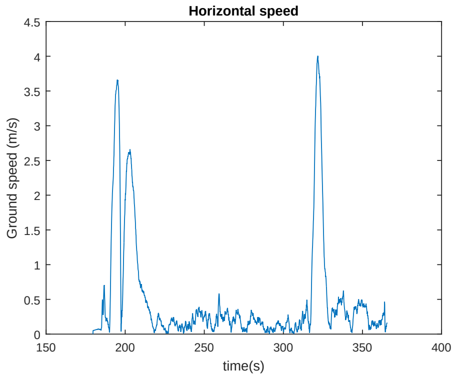
During this test calibration problems with the compass and the accelerometer appeared. The UAV was not as stable as wished because of this. With a re-calibration the problems were solved.

9.2.4 Test 4

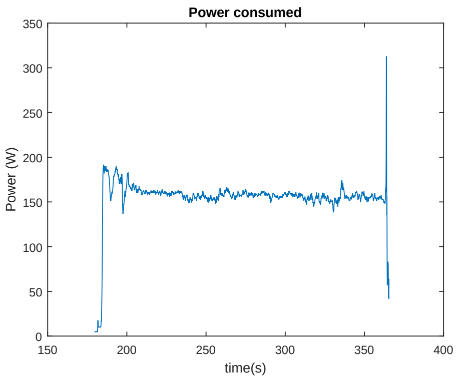
Hovering flight In this sections the hovering flights are analysed using the code elaborated. Only the graphics of one of the flights is shown, the others can be consulted in Annex J.2. The real path followed during the first flight, the speed and the consumption can be seen in Figure 9.2.2.



(a) Path followed.



(b) Speed.



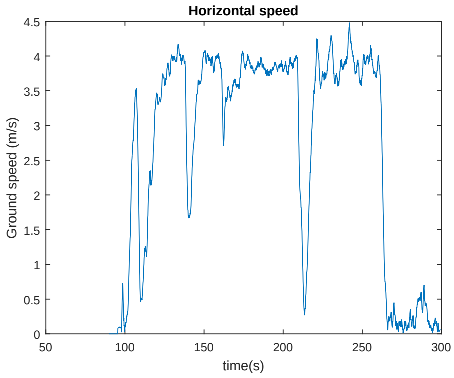
(c) Power consumption.

Figure 9.2.2: Results for the first hovering flight.

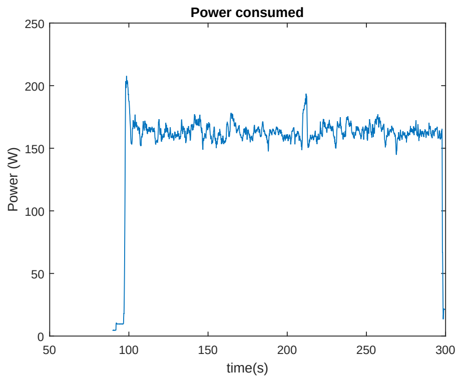
Forward Equally as in hovering flight, only the graphs of one of the flights is shown, to see all of them see Annex J.3.

For one of the flights performed at 4 m/s, the result can be seen in Figure 9.2.3.

(a) Path followed.



(b) Speed.



(c) Power consumption.

Figure 9.2.3: Results for the first 4 m/s flight.

9.2.5 Test 5

Flying the UAV with small quantity of energy available produces and automatic landing. When analysing the data flash logs of the UAV with Mission Planner, it is verified that the failsafe option has been activated and used, as can be seen in Figure 9.2.4.

-2	-1	0	TimeUS	Subsys	ECode	
6478	2017-04-06 10:5...	ERR	226167643	6	1	FAILSAFE_BATT

Figure 9.2.4: Review of the errors of the failsafe test.

9.2.6 Test 6

In order to produce a crash without damaging the UAV, what is done is to give unequal thrust to the engines during the take off, so the UAV knock over before the take off. It can be seen that when the crash happens the engines stop, avoiding more damages to the UAV and its surroundings. When analysing the data flash log, the error and behaviour shown in Figure 9.2.5 appear.

```
ERR, 99680520, 12, 1
MSG, 99680531, Crash: Disarming
```

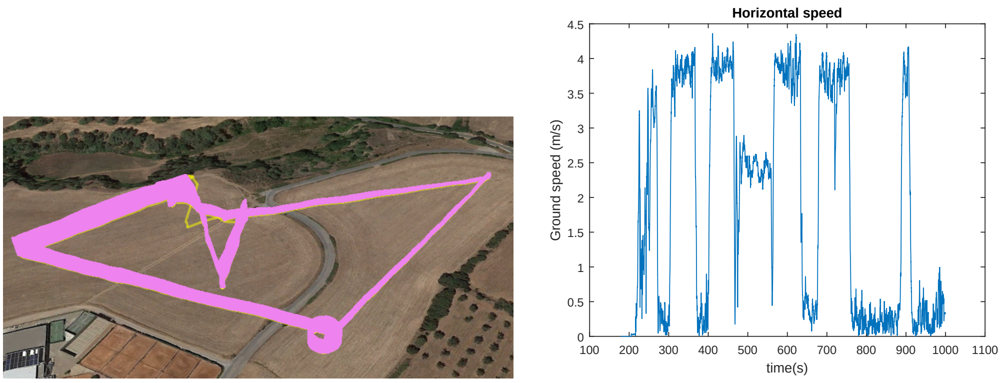
Figure 9.2.5: Crash detection and disarming message on the data flash log of the test.

9.2.7 Test 7

The communication system has been powered on and its behaviour checked satisfactorily. With the good results of this test, Test 8 can be carried out.

9.2.8 Test 8

This test has been done and its results are satisfactory. This route has been done at slow speed in order to make the UAV flight a long time so the communication system could send more messages. The speed and the duration of the flight together with the path followed can be seen in Figure 9.2.6.



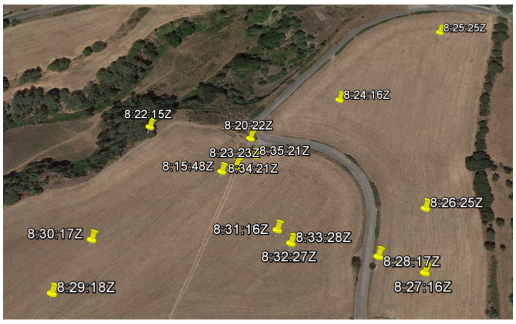
(a) Path followed. (b) Speed.

Figure 9.2.6: Results for the communication system test.

The duration of the flight has been of approximately 16 minutes, so more or less the same number of messages should be received. Checking the data base created, the messages can be seen. The last positions of the UAV can be consulted in a map. All this data is shown in Figure 9.2.7.

06/04/2017	8:20:22Z	41.59451	2.016189	24.761	99
06/04/2017	8:22:15Z	41.59465	2.015149	24.009	97
06/04/2017	8:23:23Z	41.59425	2.016061	23.713	93
06/04/2017	8:24:16Z	41.59488	2.017114	23.421	88
06/04/2017	8:25:25Z	41.59563	2.018321	23.029	83
06/04/2017	8:26:25Z	41.59387	2.017808	22.811	79
06/04/2017	8:27:16Z	41.59339	2.017709	22.644	74
06/04/2017	8:28:17Z	41.59351	2.01733	22.436	69
06/04/2017	8:29:18Z	41.59328	2.014541	22.228	65
06/04/2017	8:30:17Z	41.59367	2.014788	22.104	60
06/04/2017	8:31:16Z	41.59372	2.016455	22.004	55
06/04/2017	8:32:27Z	41.59362	2.016575	21.866	50
06/04/2017	8:33:28Z	41.59362	2.016574	21.771	45
06/04/2017	8:34:21Z	41.59434	2.016237	21.717	40
06/04/2017	8:35:21Z	41.59434	2.01624	21.597	35

(a) Messages at the data base.



(b) Position points.

Figure 9.2.7: Messages received.

9.3 Comparison between real and theoretical power

9.3.1 Hovering flight

With the data obtained from the flights, the mean power consumption at hovering can be calculated and compared to the theoretical one, as shown in the following table.

Power Test 1 (W)	158.83
Power Test 2 (W)	156.83
Power Test 3 (W)	157.83
Mean real power (W)	157.83
Theoretical power (W)	149.38
Relative error (%)	5.35

Table 9.3.1: Deviation of the power calculated in hovering flight.

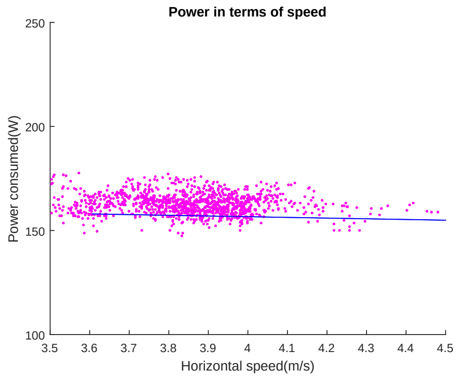
It can be seen that the real power consumed is 5.35% higher than the predicted one. This can be due to, mainly, two factors:

- Approximations done during the calculation of the theoretical power.
- External interferences during the flight of the UAV.

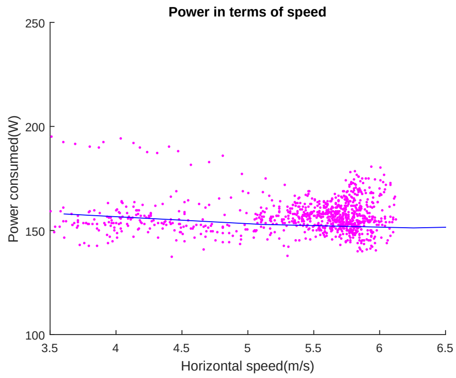
The error produced is acceptable, so the results are satisfactory and the UAV can accomplish the mission it was designed for.

9.3.2 Forward flight

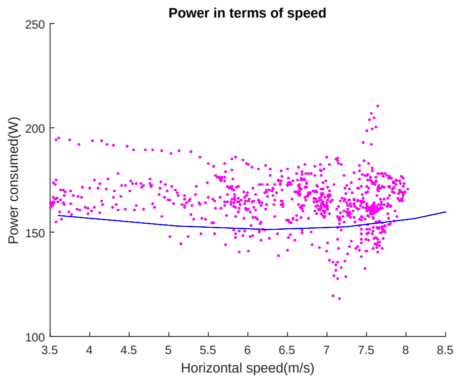
Now the deviation between real and theoretical power for forward flight is calculated. In Figure 9.3.1, is possible to see the power in terms of speed for the different tests. The purple points are the ones captured during the flight and the blue graph is the line correspondent to the theoretical power consumption.



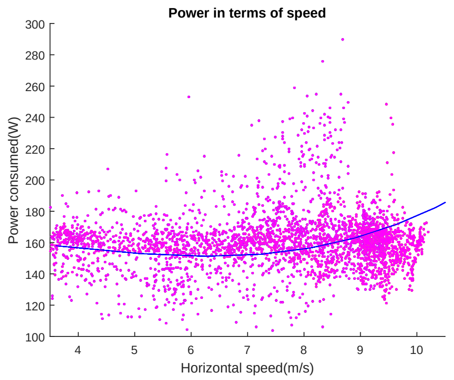
(a) 4 m/s.



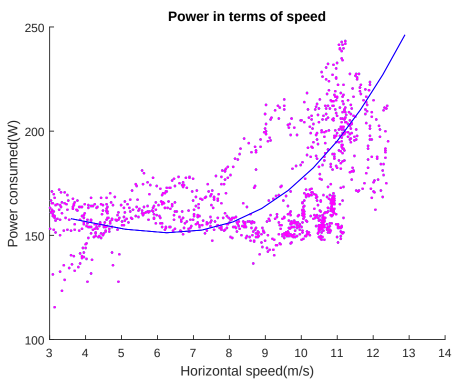
(b) 6 m/s



(c) 8 m/s



(d) 10 m/s



(e) 12 m/s

Figure 9.3.1: Power against speed.

It can be seen that the real consumption follows approximately the theory. To know the error in the graphs, what will be done is to find the error at 10 different points and then calculate the mean error. The results can be consulted in Table 9.3.2. This numbers have been obtained with the flight analysis algorithm, that can be consulted in Annex F.2.

Flight	**Error produced (%)**
Flight at 4 m/s	3.35
Flight at 6 m/s	4.23
Flight at 8 m/s	6.56
Flight at 10 m/s	3.99
Flight at 12 m/s	3.37

Table 9.3.2: Real and theoretical power for forward flight.

Real and theoretical power calculated are very close for all the flights performed. The results are satisfactory and energy consumption is in the range of foreseen.

10 | Budget overview

In this section the cost of the project is shown in general terms. To see the breakdown of it, please refer to the Budget document.

Engineering fees	9150€
Prototype parts	741€
Total cost of the project	9891€

Table 10.0.1: Budget overview

11 Environmental impact study

In this section the environmental aspects of the development of the projects are exposed.

11.1 Design

This stage of the project is important because is when important decisions that affect the environment take place. The modular design of the UAV makes it easy to replace parts of it when needed, reducing the waste produced. It also has been design as optimal as possible from the point of view of energy consumption.

11.2 Parts manufacturing

The worst part of the project remains in the manufacturing of some of the parts of the UAV. Specifically, in the electronic parts, which have chemical components. In this project the electronic components used follow the european directive 2011/65/CE (Restruction of Hazardous Substances), that can be consulted in [43].

11.3 UAV use

The use of the UAV in the experimentation part of the project has a small impact in the environment. It affects it in terms of acoustics and energy consumption.

11.4 Dismantling

After the usage of the UAV, it could be easily reprogrammed to do another tasks as hobby or photography purposes. However, if there are parts that are not useful they have to be treated according to the current law. Specifically, in the case of the battery and the electronic components, the directive 2012/19/CE (Waste Electrical and electronic Equipments) has to be followed [44].

12 | Future developments

This project has dealt with the design of an UAV to test the possibility of it to perform a specific mission. Although a lot of work has been done, future projects can improve the solution developed. In this page the developments to do are proposed and briefly explained.

- Payload module: Elaboration of a payload package that could be opened when needed, delivering the package to the interested person. This payload would need to adapt to the UAV designed, although another UAV can be designed using the methodology created in this project.
- Frame manufacturing: In this project the frame has been chosen from the market. However, it might not have been the best choice. For this reason, a frame designed specifically for the components of the UAV could be of interest. It would include the battery support and the communication system case.
- PV system: PV systems would need to be revised according technology developments in order to see its improvements and do again an usefulness study for an implementation in an UAV.
- UAV station design: A station for the UAVs where they can be stored and charged would need to be designed. A communications network between stations to exchange information regarding calls for help and UAVs availabilities have to be designed. The coordination between the station and the UAVs has to be stated as the doors will need to open when the UAV takes off and lands. PV systems would need to be installed in the station to charge the UAVs. All this has to be done diminishing the environmental impact in the mountainous region where it will be placed.
- UAV intercommunication: More than one UAV would work in the same region. For this reason, a good communication net has to be designed to stablish an intelligent collaboration between them. For instance, a second UAV can be activated if the first one has had an accident. Also, the network can avoid collisions in case of two UAVs flying close.

13 | Conclusions

In this section the conclusions are stated. The technologies that were decided to be used at the beginning of the project are cited here again in order to see if they have accomplished its function or not.

1. **Multi-rotor UAV.** The designed UAV is a quadcopter, that is a multi-rotor UAV. With this frame the capability of the UAV to maintain both forward and hovering flight is accomplished.

2. **Suitable selection of the battery and possibility to include a photovoltaics generation system.** One one hand, the battery has been selected doing a proper calculation of the power consumption. It has not been possible to test that the UAV has a range of 10 km because of the restrictions in the law presented in section 14. However, as it has been proved that the calculation of power is correct, this range is sure to be achieved with the battery selected in the UAV Design Chapter. On the other hand, a photovoltaics generation system has not been included in the UAV due to the fact that the available space is not large enough to produce benefits of its implementation nowadays.

3. **Flight optimization.** A flight optimization program has been created. This program calculates the optimum path taking into account the wind interference in the UAV trajectory. Implementing this optimization and according to the power consumption of the UAV, the energy saving achieved has been as high as 12 %. This figure can be even better depending on the route and wind conditions. The program also creates the Waypoint file the UAV has to follow, so it also contributes to make the system more autonomous.

4. **Autonomous flight.** With the selection of the flight controller and the elaboration of the algorithms to create the waypoint files, the UAV can fly autonomously without any problem.

5. **Wireless communication.** A communication system has been implemented using a satellite communication module. It is the only communication system that could work

inside the area of work of the project in the range specified. It has a limitation on the size of the message, but it works satisfactorily for the mission of the UAV.

6. **Generation of a map with the positions of the UAV and creation of a database.** This algorithm has been generated satisfactorily. Using a computer the personal in charge of the UAV can see its last position in a map and can also have a proper historical data about the flights the UAV has performed, when, where, etc.

7. **Design of the management and control electronics and proper configuration of the flight.** The selection of the components has been done in order to take profit from all the energy available at the battery. This fact makes possible that the energy of the UAV is managed efficiently in order to achieve the target. However, if the UAV can not achieve the target and runs out of energy, the flight controller has been configured to effectuate a landing in safe conditions.

8. **Crash detection.** In case of crash, the event is detected and the engines stopped to avoid major damages. Equally to the failsafe option, this is obtained thanks to the proper configuration of the flight controller.

In short, the requirements have been accomplished satisfactorily and the problems found during the elaboration of the project have been solved.

14 Regulation

During the elaboration of this project it was not needed to enter inside the regulations of the manufacturing of the parts of the UAV that were assemble, as this depend on the manufacturer of the product. The dismantling of the UAV after this project will be done according to the exposed in section 11.4.
The part most exposed to regulations in this project is the flight of the UAV, that has been done according to the Spanish Law 18/2014 art50, that can be found in reference [45].

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